GROUND WATER DEPTH PREDICTION FROM SATELITE DATA

A Thesis Submitted
in Partial Fulfilment of the Requirements
for the Degree of
MASTER OF TECHNOLOGY

By
PRADEEP SINGH

to the
DEPARTMENT OF CIVIL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY, KANPUR

DECEMBER, 1980

To all those who made the 'ARYABHATTA' and the 'BHASKARA' possible

CERTIFICATE

This is to certify that the work GROUND WATER DEPTH PREDICTION FROM SATELLITE has been carried out under my supervision and has not been submitted elsewhere for a degree.

December, 1980

(K.K. Rampal)
Assistant Professor
Department of Civil Engineering
Indian Institute of Technology
KANPUR, INDIA

ACKNOWLEDGEMENT

I wish to express my gratitude to my thesis guide, Dr. K.K. Rampal, for his expert guidance and motivation, to my colleagues Mr. Shashi Kumar, Mr. Adalat Ali and Mr. A. Chaturvedi for their invaluable help and encouragement, to Mr. Verma and Mr. O.P. Awasthi for their careful typing work, and to many other friends, who helped in many ways in the completion of this thesis.

Pradeep Singh

December, 1980

(PRADEEP SINGH)

Department of Civil Engineering
Indian Institute of Technology,
KANPUR, INDIA.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

SYNOPSIS

Dissertation on

GROUND WATER DEPTH PREDICTION
FROM SATELLITE DATA

Submitted in partial fulfilment of the
requirements for the degree
of

MASTER OF TECHNOLOGY IN
CIVIL ENGINEERING

by

Pradeep Singh
Department of Civil Engineering
Indian Institute of Technology, Kanpur

December, 1980

This project explores the possibility of shallow ground water depth prediction from satellite data. Two methods are used for this purpose the computer compatible tape method and the Micro-densitometer method. Both methods are based on the fact that reflectance characteristics of a particular soil cover vary with variations in the ground water depth. Calibration curves between reflectance units (CCT method) or light density (densitometer method) and water depth, are developed from the field data and these curves are used for prediction of ground water depths. The CCT method is more accurate than the other method. It was found that these methods are not applicable for water depths over 10 m, or for hilly or built up regions. Very encouraging results were obtained in

The prediction of ground water depths in alluvial soil (Gujrat region) in depths less than 10 m. For such regions this study establishesthat the for making ground water contour maps of large areas, the most economical and convenient method is a satellite survey.

CHAPTER - 1

INTRODUCTION:

1.1 Basic Principles: The objective of this thesis is to explore the possibility of predicting shallow water depths from satellite data. This study is aimed at providing a more economical and convenient medium (i.e., a satellite survey) compared to ground surveys for making ground water maps of large areas.

The area selected for study encloses a part of Rajasthan and a part of Gujrat (about 185 Km. x 185 Km.). A broad geological classification of this area is given in Fig. 1. The satellite data pertaining to this specific area was obtained by LANDSAT in the form of a black and white photo negative, and Computer Compatible Tapes (CCT). This satellite data - the imagery and two CCTs - were procured by the Indian Space Research Organization (ISRO), from the EROS Space Centre, South Dakota, USA.

Remote sensing is the science of obtaining khowledge without physical contact. The remote sensing satellite by the use of Multi-Spectral Systems (MSS) can gather such 'knowledge' from an altitude of several hundred kilometres (920 Km. for LANDSAT), by scanning the land masses underneath and recording the neglected solar radiation (or 'reflectance') in different wave-bands. For water studies, we use the reflectances recorded by the MSS in the infra- red region or band - 7 (0.8-1.1 m wave- length) because in this band water appears black on the positive print due to strong absorption bands in the near Infra-red part of the spectrum. For a particular soil in a given area, the variations in shallow water

depths alter the tone of the ground surface and these variations, most discernible in Band - 7, alter the reflectances of the same ground surface depending upon the proximity of the ground water to the ground surface. Hence the variation in reflectances, of the same ground surface is related to the variation in the ground water depths. By measuring the ground water depths by bore holes etc. at a number of distributed points in the given area and by recording the corresponding reflectances from the available satellite data, we can study the correlation and plot a curve of reflectance versus ground water depth. This is a calibration curve, and it can also be called a calibration - prediction curve because it can be used to predict the ground water depths at different points in the given area knowing the corresponding reflectances.

Two techniques based on this principle have been employed in this research study for the prediction of shallow ground water depths. One uses a micro-densitometer and the other is based on the application of magnetic tapes (CCTs). The CCT approach required an extensive use of the DEC-10 computer available in IIT Kanpur.

The promising results obtained in this study highlights the scope of satellite application for predicting shallow water depths. For a large area survey like a state survey or a national survey for marking ground water depth contours, it is obvious that the most economical and convenient option is a satellite survey.

* * *

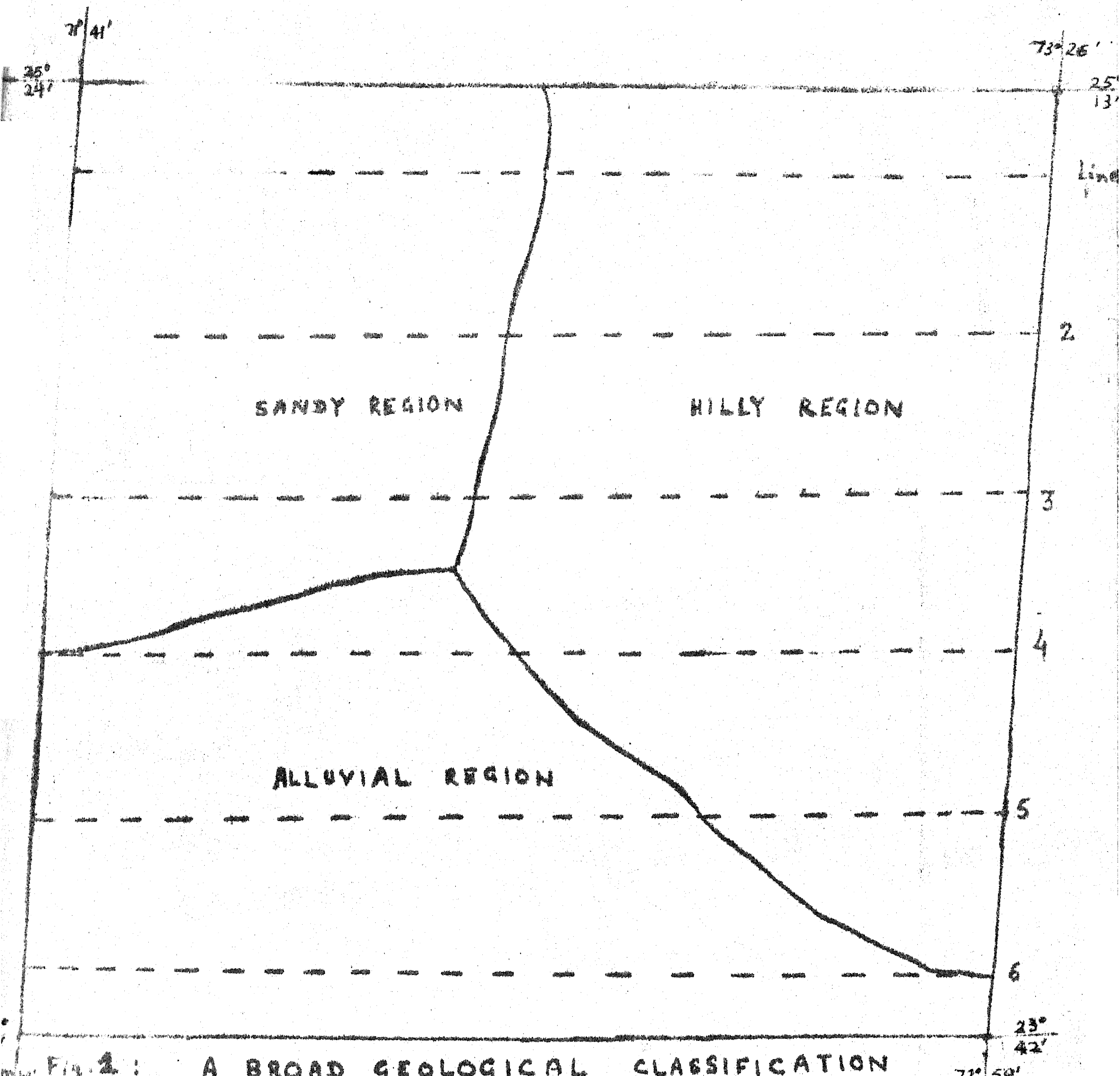


Fig. 1 : A BROAD GEOLOGICAL CLASSIFICATION

CHAPTER - 2

MAGNETIC TAPE METHOD:

2.1 Computer Compatible Tape (CCT) Approach:-

The data collected from a Multi spectral scanner (MSS) on a aircraft or satellite can be stored on a Computer Compatible Tape after being processed at a ground data collection centre. The MSS system collects ground reflectance data by scanning along lines perpendicular to its flight path and recording reflectance values as 'pixels' along each 'line'. The resolution of a pixel in Landsat-3 is about 80 m. After being processed at the ground station to eliminate undesirable interferences or 'noise', the data or 'signals' is recorded on a CCT in the form of 'records', The 'pixels' or reflectances are recorded in 'bits' on a CCT in the binary mode.

2.2 CCT Storage Mode:

Information is stored in a CCT in the form of 'records'. Each record represents one line scanned by a satellite in a given imagery. Each record is subdivided into 'words' - a smaller storage unit, i.e. And each word is subdivided into 36 'bits', a bit being the smallest storage space on a CCT. Each bit stores one binary number. In our case, one word in the CCT Stores four pixels, each pixel occupying seven bits of space (hence the maximum reflectance value cannot exceed $2^7 = 128$). The reflectance values range from 0 to 128.

As the MSS system records data in Bands 4, 5, 6 and 7. The same pixel is recorded on a '800' density or '1600' BPI tapes in four different parts in the four wave bands. Each '800' density

CCT contains two sections or 'files', and each file contains data of the same one imagery in a given wave band. Thus to record the same imagery in Bands 4, 5, 6, 7 seperately, two '800' density CCTs are required, each wave band confined to one file on a tape.

The CCT containing Band - 7 part of the imagery was used for ground water study in this study because variations in ground water profile are most discernible in Band - 7 (0.8-1.1 µm wavelength);

A Computer program (see Appendix No. I) was developed which gives the line number and the pixel number of a particular spot on the imagery or a band map of the given Rajasthan - Gujrat region for the given latitude and longitude coordinates of this particular spot. Hence, to read the reflectance value from a CCT at any given point on a imagery, first the latitude and longitude of this point are determined from the topo sheet and these coordinates are fed into the computer program to get the required line number and pixel number of the given point. Once the line number and pixel number are known, the CCT is used to read the records on the tape till we reach the required record (or line scanned by the MSS) Next we activate a computer program (see Appendix II) which reads the record, converts the data from binary to decimal mode and prints the given reflectance (or 'pixel' scanned by the MSS).

2.3 Central pixel Method & Grid Averaging Method:

Four sets of correlation were attempted between reflectance and ground water depth. In the first case or the so called the 'central pixel method', only the exact pixel corresponding to the given latitude and longitude coordinates of a given point on a land map or imagery,

was selected and its reflectance value was correlated with the corresponding water depth.

In the Grid Averaging Method, we take a number of pixels on either side of the central pixel and take the arithmetic mean of the reflectances of these pixels which form a square or grid with the central pixel occupying the centre position. It is obvious that for a square grid, each side of the grid must have an odd number of pixels. Hence we can have a grid with 3 pixels on each side, 5 pixels on each side, 7 pixels on each side etc. In this study these three grid values were chosen (3, 5, 7 pixels, i.e.). It can easily be seen that in the case of the grid approximation method for 3, 5, 7 pixels making up the grid sides we will have to take the arithmetic mean of 9, 25 and 49 reflectance valves respectively to get the representative reflectance of each grid. For a large number of control pixel points, manual computations being time consum ing for grid averaging at each point, a simple computer program was used which gave the representative reflectances for both central pixel method and Grid Averaging Method (5, 6, 7 pixels grids) for each observation point.

After this step is completed, knowing the latitude and longitude of a given observation point, four representative reflectances corresponding to this observation point (one for the central pixel , the other three for the 5, 6 and 7 pixels size grids) are computed. The next step is the preparation of reflectance versus depth curves.

2.4 Calibration:

The four representative reflectances, obtained from the previous step, were plotted individually against observed ground water

correlations were attempted. After the points were marked on each graph the next step was curve fitting. A qualitative inference about the nature of the calibration curve fot the magnetic tape approach, was deduced from basic principles. As water appears black in Band 7 the shallower the water table is the more affected the ground surface would be from the moisture proximity.

Hence for lesser water depth the same ground surface will give lesser reflectance and for deeper depth the reflectance will be greater. For a surface water body like a lake, the reflectance will be zero, the minimum reflectance value. Hence we have an exponential growth curve of increasing slope, between reflectance values and the corresponding water depths. Mathematically, the equation of such a calibration curve fitted is :-

$$y = e^{bx+c} \qquad - \qquad - \qquad \text{(II)}$$

where 'b' and 'c' are constants,

y = reflectance,

x = ground water depth

In order to fit a calibration curve obeying Equation (II) in the four sets of graphs between the representative reflectances and the observed ground water depths, the method of least squares was adopted.

<u>Evaluation of 'b' and 'c' in Equation (II):</u>

Taking the natural logarithm of both sides in Eqation (II),

$\log_e y \doteq bx+c$

Let $Y = \log_e y, \quad b = BB, \; c = cc$

$Y = BB\,x + CC$

It can easily be established that the normal equations are,

$$\sum Y = BB \sum x + n\, CC \quad - \quad - \quad - \quad (III)$$

$$\sum xY = BB \sum x^2 + CC \sum x \quad - \quad - \quad - \quad (IV)$$

where n = number of observed points.

The values of 'BB' and 'CC' can be found by simultaneously solving Equation (III) and (IV) by inserting the observed values of 'X' and 'Y'.

Once 'BB' and 'CC' are known the standard error, , for the "fit" determined from:-

$$\sigma = \sqrt[2]{\frac{\sum_{i=1}^{n} (x_i - \bar{x})^2}{n - 1}}$$

After the 3-σ test had been applied, the coefficient of correlation was determined to find whether there was any correlation between 'x' and 'y' and if so, how good it was. The correlation coefficient is defined as:

$$r = \frac{\sum (x - \bar{x})\ (y - \bar{y})}{\sqrt[2]{\sum (x-\bar{x})^2 \sum (y-\bar{y})^2}}$$

The value of 'r' can vary from -1 to +1. A negative 'r' indicates that 'y' decreases with increase in 'x'. If $r = 0$, it indicates an absence of correlation. If $r \doteq 0.5$, a weak correlation exists; if $r \approx 0.8 - 1.0$, a good correlation is concluded (subject to the usual standard statistical tests with the given level of confidence).

Results: In this study, with the help of a computer program (see AppendixIII), the calibration curve equations, standard deviations and coefficients of correlation were determined for the four plots in the magnetic tape method for the Gujrat region. These results are given in Table - 1.

Table - 1

METHOD	CALIBRATION CURVE EQUATION $y = c^{BBx+cc}$		STANDARD DEVIATIONS		CORRELATION COEFFICIENT
	BB	CC	for 'x'	for 'Y'	'r'
Central Pixel	0.20175720	1.92411720	2.047	0.440	0.9389
3 pixels grid	0.16010590	2.41294530	2.047	0.368	0.8916
5 pixels grid	0.07443128	3.08453320	2.047	0.179	0.8523
7 pixels grid	0.03375640	3.46898590	2.047	0.125	0.5544

The field data for the Gujrat region used for obtaining these results are given in Table 2(Appendix IV).

The field data for the Rajasthan region - used in making reflectance vs. depth plots (see fig. 2-5) by central pixel method and 3 pixels, and 5 pixels linear averaging methods - are given in Table 3.

No appreciable correlation was found between reflectance and depth in the Rajasthan region after inspecting figs. 2-5.

Table – 2

Field data Gujrat region (CCT Method)

Sl. no.	Longitude (Degrees)	Latitude (Degrees)	Line No.	Pixel No.	Reflectance				Depth (m.)
					Central pixel method	3-pixel grid	5-pix. grid	7-pixel grid	
1.	72.850000	24.340000	1436	2195	19	27	31	35	5.0
2.	72.425000	23.915000	2163	1764	59	57	45	42	10.0
3.	72.366666	24.266666	1656	1524	21	24	31	35	5.8
4.	72.366666	23.916666	2174	1679	34	43	42	48	8.7
5.	72.020000	24.520000	1357	910	27	26	32	39	6.8
6.	71.810780	25.354423	172	241	58	59	47	43	9.9
7.	71.866667	24.300000	1721	781	24	39	41	45	7.7
8.	71.625000	25.363000	437	167	19	22	30	36	4.8
9.	71.[illegible]	24.067376	2048	1171	24	37	40	47	5.4

Table - 3

Field data - Rajasthan region
(Longitudes and Latitudes of these field points are given in Appendix V.)

Sl. No.	Line No.	Pixel No.	REFLECTANCE Central pixel	3 pixels average	5 pixels average	7 pixels average	Measured depth (m.)
1.	179	242	63	47	44	42	9.90
2.	235	928	22	41	44	47	3.46
3.	236	1328	66	59	58	49	8.64
4.	248	1256	41	42	43	49	6.23
5.	261	1179	25	44	47	48	8.66
6.	271	1296	58	51	50	42	2.11
7.	278	764	34	38	41	41	5.72
8.	285	1208	59	45	42	41	8.45
9.	286	825	27	40	45	47	6.90
10.	299	1288	39	39	39	44	8.16
11.	328	607	62	52	50	47	5.90
12.	337	609	35	31	42	46	2.99
13.	338	776	38	39	39	45	5.69
14.	340	644	48	52	43	39	7.72
15.	351	849	68	63	51	46	3.88
16.	385	935	90	29	36	39	8.27
17.	419	630	45	41	38	32	3.00
18.	426	1136	63	57	55	47	6.38
19.	436	883	22	33	38	42	8.27
20.	438	167	27	31	44	47	4.80
21.	447	185	61	62	50	45	6.39

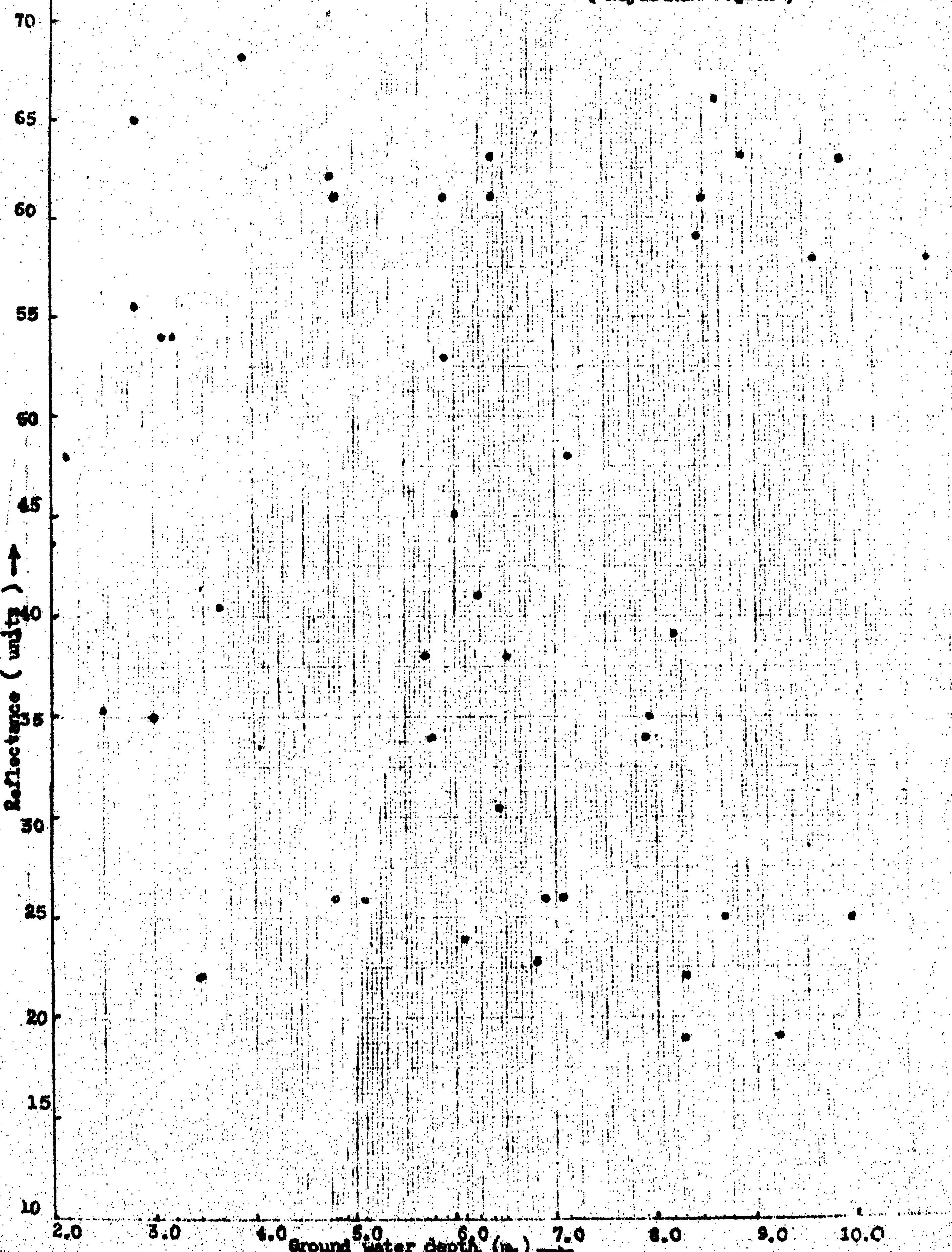
Contd. Table – 3

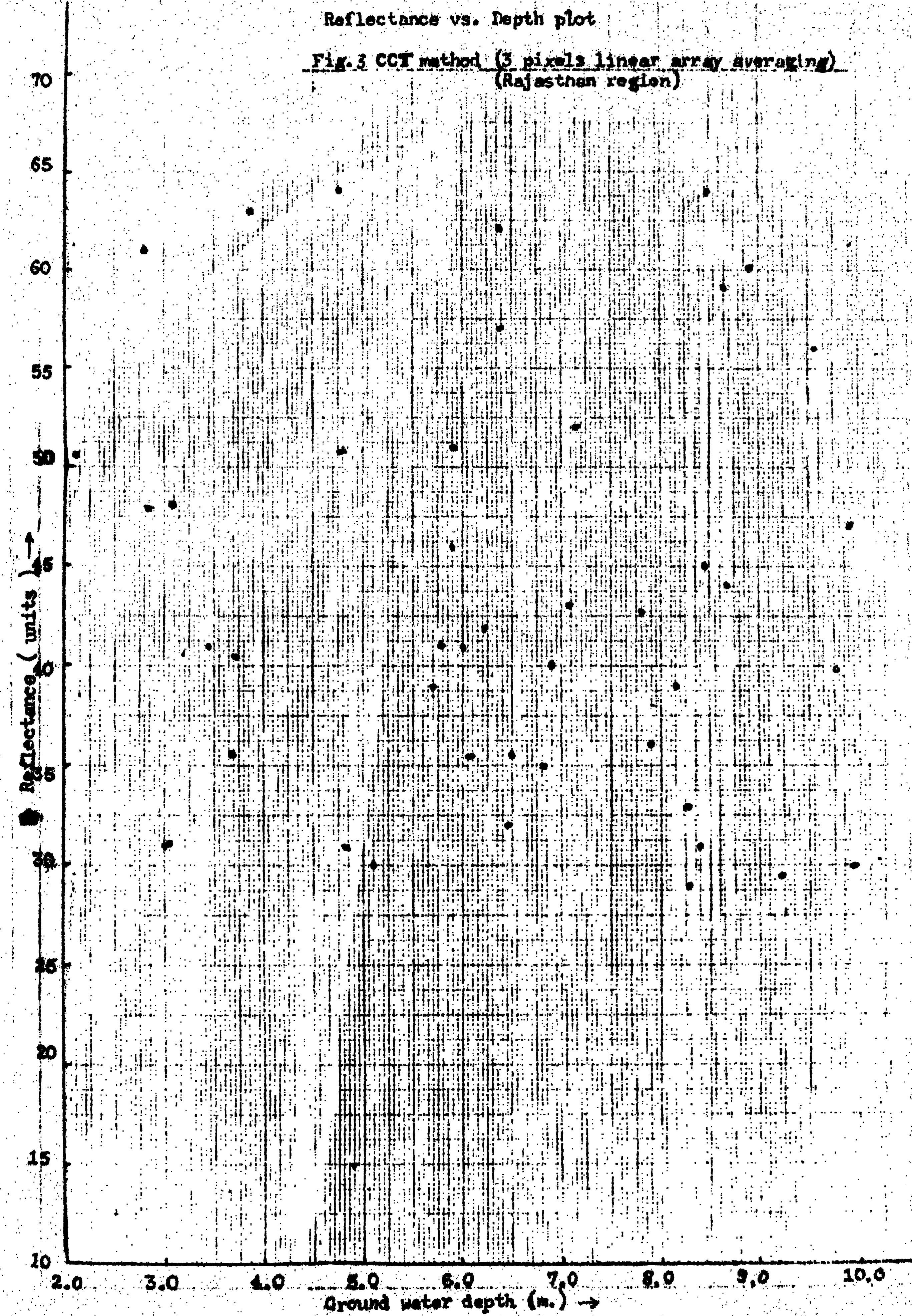
Sl. No.	Line No.	Pixel No.	REFLECTANCE Central pixel	3 pixels averavge	5 pixels average	7 pixels average	Measured depth (m.)
22.	455	1035	69	68	58	53	8.75
23.	456	754	56	46	42	40	2.77
24.	460	675	54	49	48	41	3.06
25.	467	1283	63	60	58	52	8.90
26.	483	909	26	43	52	55	7.80
27.	489	734	65	61	49	46	2.80
28.	479	631	62	64	58	44	4.75
29.	509	1237	31	32	33	39	6.45
30.	519	1177	19	29	33	34	9.20
31.	525	724	25	30	42	49	9.95
32.	533	1168	38	36	36	30	6.50
33.	553	737	41	36	51	56	3.67
34.	563	1232	53	47	47	40	5.89
35.	629	435	24	36	42	46	6.10
36.	646	692	27	30	43	48	5.10
37.	709	216	54	41	38	37	3.20
38.	900	414	58	57	45	42	9.53
39.	1251	314	9	15	20	23	4.90
40.	1360	909	23	35	38	39	6.80
41.	1682	402	62	53	48	49	4.80
42.	2047	776	34	37	37	43	7.90
43.	2127	494	35	32	44	50	8.40

Reflectance vs. Depth plot

Fig.2 • CCT method (Central pixel method) •

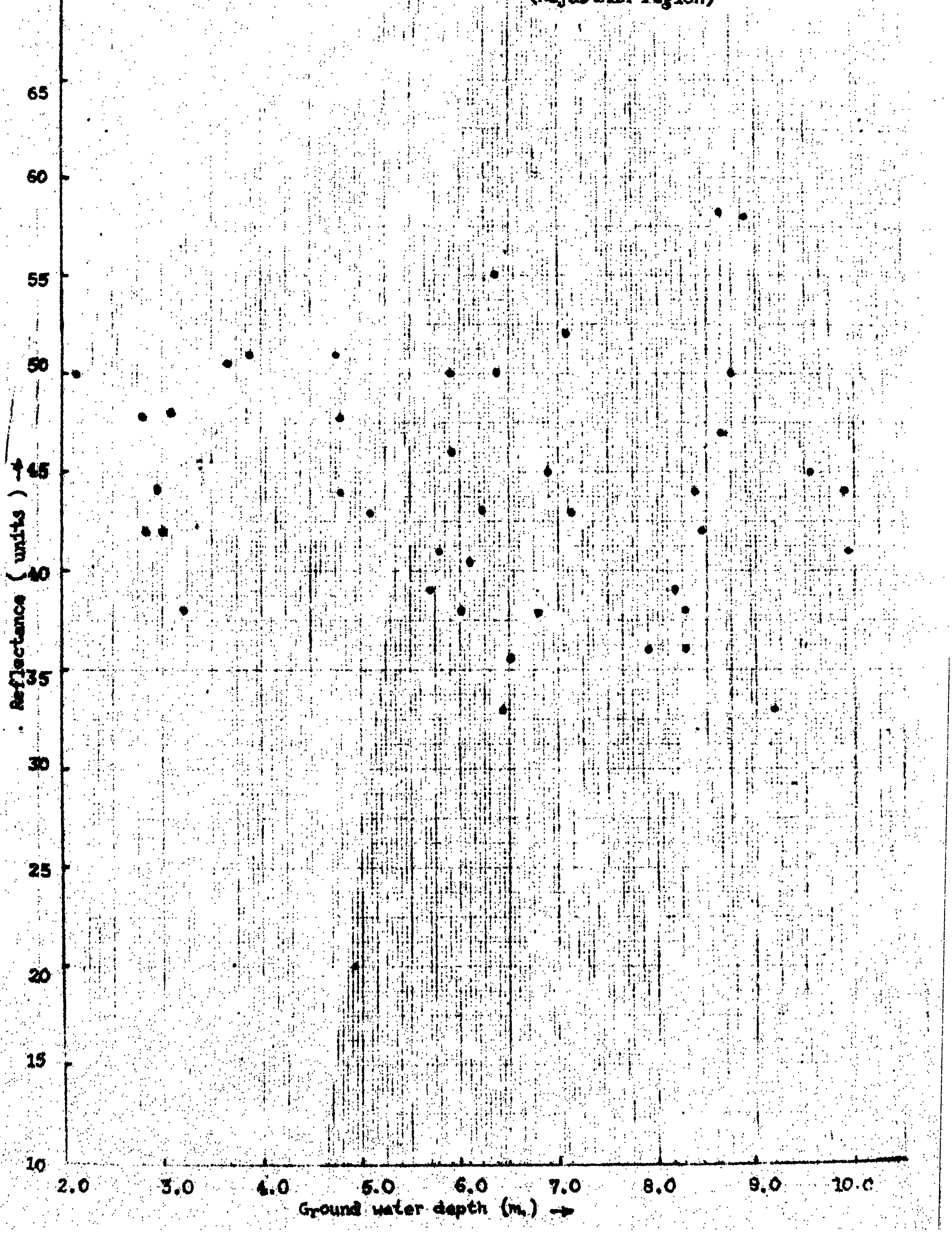
(Rajasthan region)

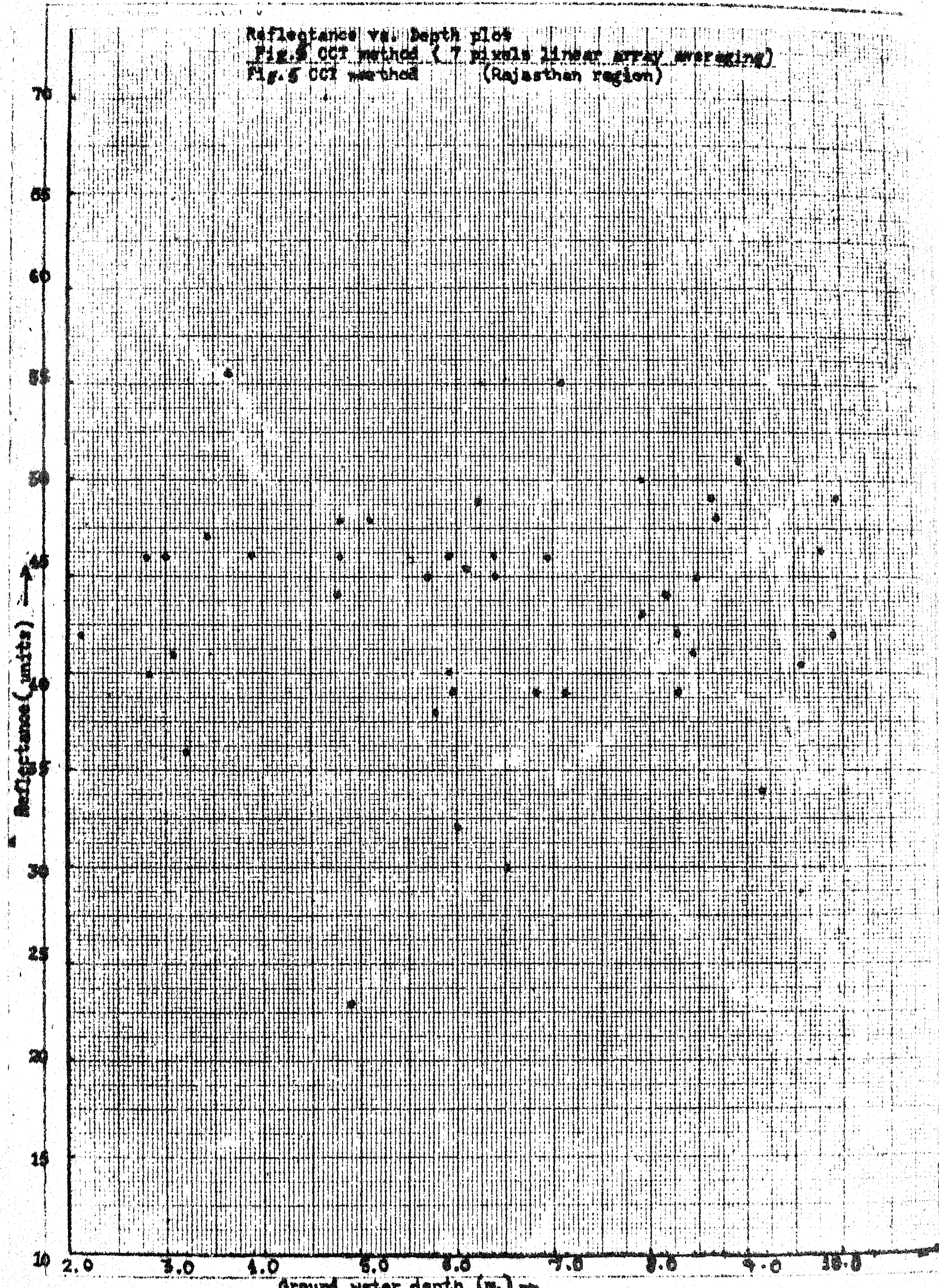



Reflectance vs. Depth plot
Fig.3 CCT method (3 pixels linear array averaging)
(Rajasthan region)
70
65
60
55
50
45
40
35
30
25
20
15
10
Reflectance (units) →
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
Ground water depth (m.) →

Reflectance vs. Depth plot

Fig. 4 CCT method (5 pixels linear array averaging)
(Rajasthan region)





Reflectance vs. Depth plot
Fig.5 CCT method (7 pixels linear array averaging)
Fig.5 CCT method (Rajasthan region)
Reflectance (units) →
70
65
60
55
50
45
40
35
30
25
20
15
10
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
Ground water depth (m.) →

Fig. 6 CCT method (Central pixel method)

Reflectance vs. Ground water depth plot

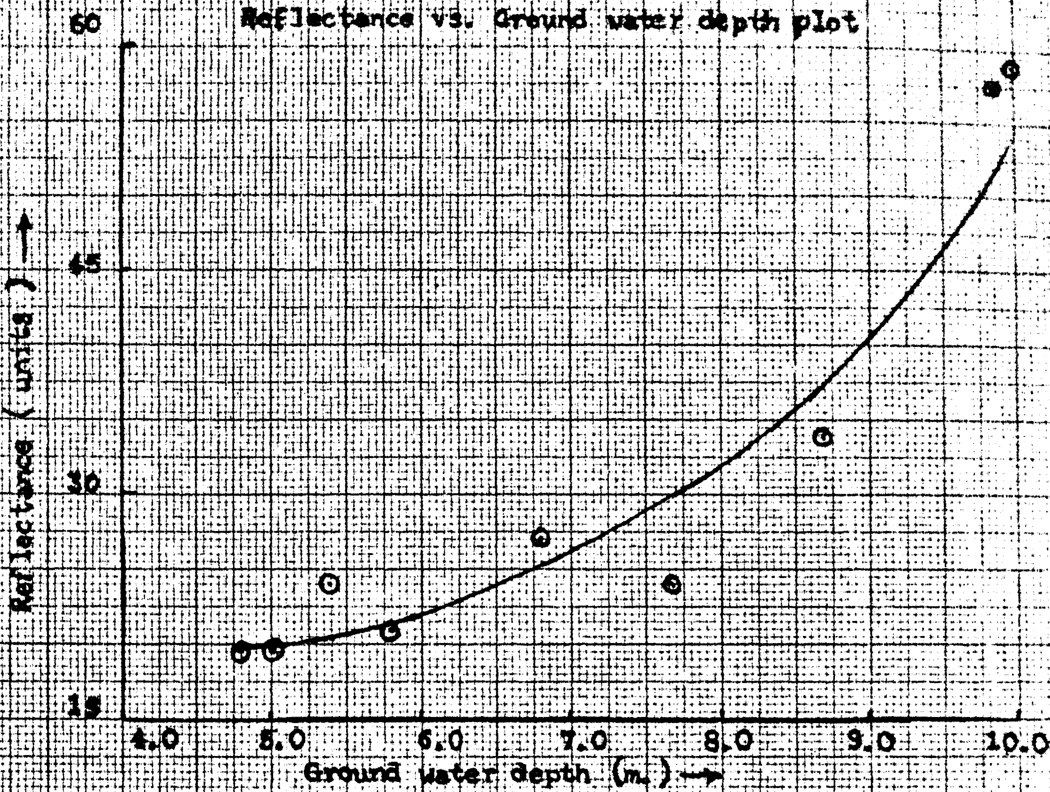
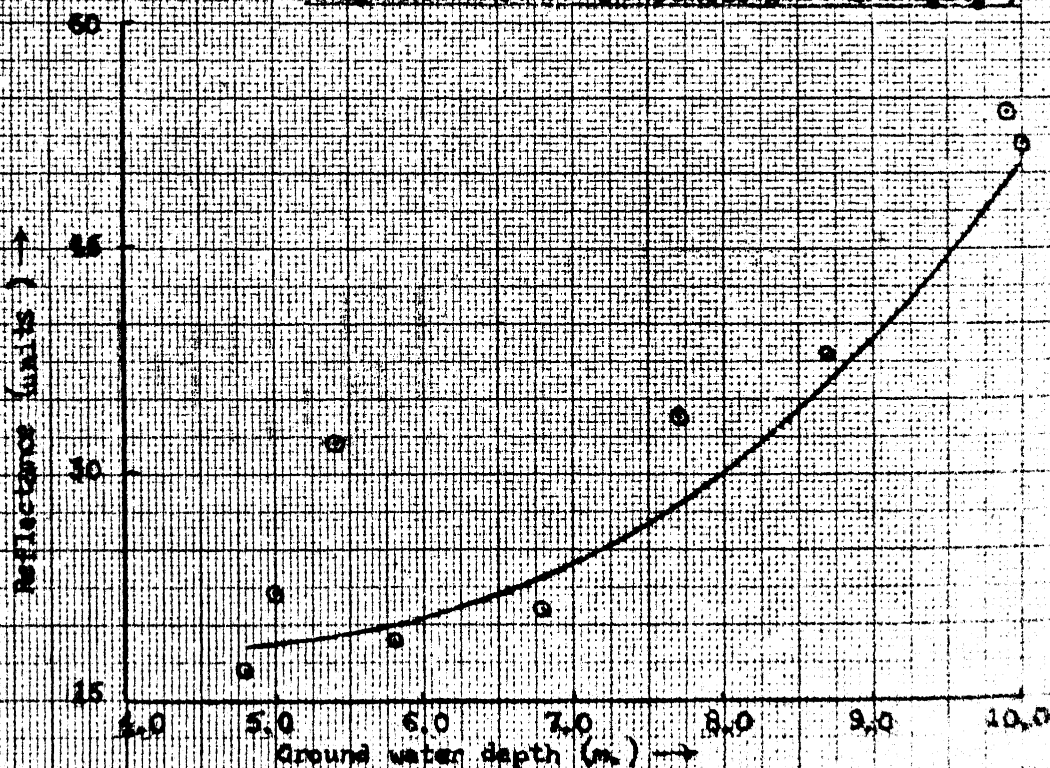


Fig. 7 CCT method (3 pixels grid averaging)



[redacted]

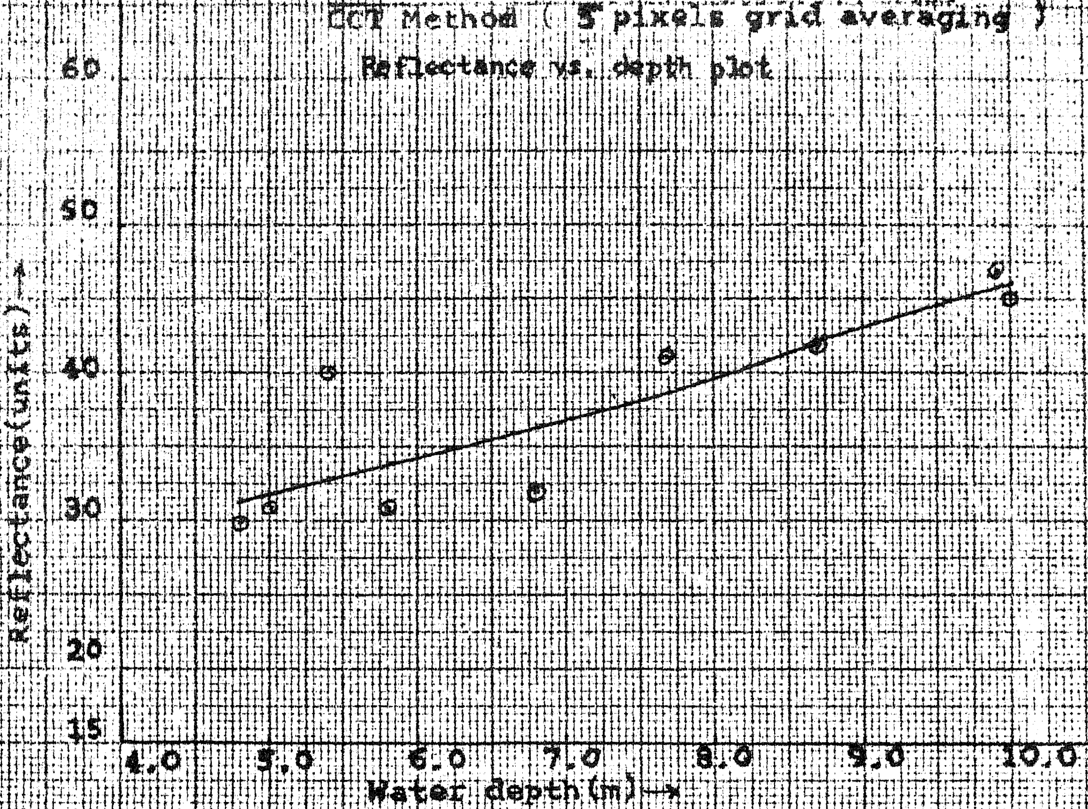


Fig.8

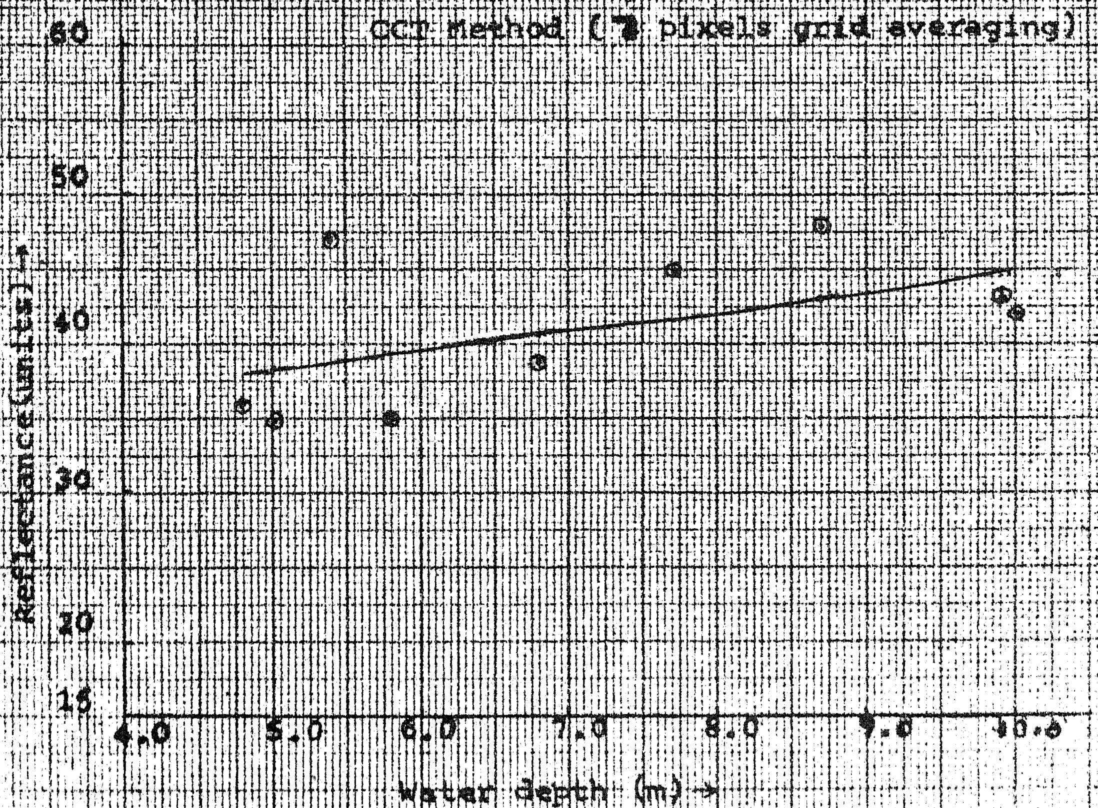


Fig.9

2.5 Prediction Process (Magnetic Tape Method):

Prediction Method:- A number of points were taken on a 1" = 4 miles scale ground water contour map of the given region and their latitudes and longitudes were determined. Using these latitudes and longitudes in the 'LATPIX' computer program (see Appendix I), the line numbers and pixel number corresponding to each point were found. Then using these line numbers and pixel numbers and the 'TAPE. FOR' computer program (see Appendix II) the corresponding reflectances (pixel values) were found. Next with the help of the calibration curves and these reflectances the corresponding ground water depths were predicted for the given set of points taken on the map. These predicted ground water depths were then compared with those indicated in the conventional ground water contour map to complete the prediction process.

To attempt a prediction of ground water depths in the Gujrat region (lower half of the given imagery) the Banaskantha district which mostly covers this part was selected. This district area was subdivided into three sub regions (see Fig. 15)for analysis. Important details about each region are given below:

Region (1) Mostly alluvial with ground water depths $<$ 10 m
Longitude 71.45° - 71.85°, Latitude ~~Latidue~~ : 24.00° - 24.50°

Region (2) Alluvial transition to hilly region, water depths $>$ 10 m
Longitude : 71.90° - 72.30°, Latitude : 24.05° - 24.50°

Region (3) Mostly hilly region with alluvial regions in minority.
Depths : variable; includes $>$ 10m, depths also.
Longitude : 72.35° - 72.70°, Latitude: 24.10° - 24.25°

Region (1) was expected to be most suitable for prediction purposes and the results of the two prediction methods - tape method & densito meter method bore this out. In Region (2) & Region (3) the methods are

unreliable because of the deep depths and hilly terrain.

RESULTS AND DISCUSSION: The field data etc. isgiven in tables 4-7.

A separate case study was taken up to show that the satellite survey methods are not useful for detecting depths deeper than 10 m. Ninetten field measurements of water depths greater than 10 m were undertaken and the prediction process using the tape method was applied (See table - 7). The following results were obtained :

N = 19 points, σ = 2.75 m

The 3 - σ test shows that we have to reject any $x >$ 8.27 m hence we reject serial no. 16 observation table - 7. Therefore, we finally get :

N=18,

Standard error, σ = 2.63 m

The high value of the standard error proved the point adequately that satellite survey methods are unreliable in depths greater than 10 m.

Region (1) : (See table - 4)

Number of observation points, N 61

Standard error, $\sigma_n = \pm$ 1.36 m

The 3 - σ test shows that we have to reject any $x >$ 4.08 m hence we reject the following two observations : x = 7.84 m (Longitude= 71.6^0, Latitude = 24.4^0) and x = 6.13 m (Longitude = 71.75^0, Latitude = 24.15^0).

After removing these two points we get :

N=59, $\sigma_n = \pm$ 0.99 m.

The standard error is $\pm$ 0.99 m. The tape method thus gives a good result in Region (1), which ismostly alluvial in nature and with water depths less than 10 m, where our calibration - prediction equations yield the best results.

<u>Region (2) :</u> (See table - 5)

$N = 61$ $\sigma = 4.23$ m

The 3 - σ test shows that we have to reject any $x > 12.69$ m, hence we reject the ten observations corresponding to serial nos 28, 31, 36, 37, 38, 42, 43, 46, 48 and 52 in table - 5.

After removing these ten points we get :

$N = 51$,

Standard error, $\sigma = 3.39$ m

Therefore, the standard error being 3.39 m, we can conclude that in Region (2) we get highly unreliable results. This region is mostly of more than 10 m ground water depth, where our satellite survey methods are not applicable.

<u>Region (3) :</u> (See table - 6)

$N = 10$, $\sigma = 1.97$ m

The 3 - σ test shows that we have to reject any $x > 5.91$ m, so we reject one observation corresponding to serial no. 10 in ~~xxx~~ table - 6.

Therefore, we have :

$N = 9$,

Standard error, $\sigma = 1.84$ m

We observe that a few points (for ex., serial no. 3 in table - 6) show large differences between predicted and interpolated depths.

This occurs most probably because the nature of the local terrain, which is hilly (extension of Mount Abu hill region). A few points show a very good agreement between interpolated and predicted depths (for ex., serial no. 9) and this could be attributed to alluvial patches in between the part of the hilly regions for ground water depths less than 10 m.

Table – 4

Field data & calculations for prediction
(CCT method: Region (1), Gujrat)

Sl. No.	Longitude (Degrees)	Latitude (Degrees)	Inter-polated Depth, D (m.)	Reflect-ance	Predicted depth, P (m.)	Deviation $x = \lvert D-P \rvert$ (m.)
1.	71.45	24.20	5.00	27	6.80	1.80
2.	71.45	24.05	9.00	25	6.42	2.58
3.	71.45	24.00	9.00	59	10.67	1.67
4.	71.50	24.25	5.00	22	5.78	0.78
5.	71.50	24.20	6.48	33	7.79	1.31
6.	71.50	24.10	6.81	36	8.23	1.42
7.	71.55	24.30	4.00	23	6.00	2.00
8.	71.55	24.20	6.67	58	10.59	3.91
9.	71.55	24.15	7.00	58	10.59	3.59
10.	71.55	24.10	7.00	51	9.95	2.95
11.	71.55	24.05	8.59	61	10.84	2.25
12.	71.55	24.00	8.18	32	7.64	0.54
13.	71.60	24.40	3.00	61	10.84	7.84
14.	71.60	24.35	4.33	24	6.22	1.84
15.	71.60	24.30	7.00	27	6.80	0.20
16.	71.60	24.25	9.00	72	11.66	2.66
17.	71.60	24.20	7.00	24	6.22	0.88
18.	71.60	24.15	7.00	26	6.61	0.39
19.	71.60	24.05	7.48	38	8.49	1.01
20.	71.65	24.05	7.06	26	6.61	0.45
21.	71.65	24.45	5.64	45	9.33	3.69
22.	71.65	24.40	4.80	25	6.42	1.62
23.	71.65	24.25	7.00	22	5.78	1.22
24.	71.65	24.20	7.00	48	9.65	2.65
25.	71.65	24.15	7.00	33	7.77	0.77
26.	71.65	24.10	7.00	38	8.49	1.49
27.	71.65	24.00	5.83	20	5.78	0.05

Contd. Table - 4

Sl. No.	Longitude (Degrees)	Latitude (Degrees)	Inter-polated Depth, D (m.)	Reflect-ance	Predicted depth, P (m.)	Deviation x = |D-P| (m.)
28.	71.70	24.50	7.44	27	6.68	0.74
29.	71.70	24.45	7.29	20	5.31	1.98
30.	71.70	24.40	6.47	25	6.42	0.05
31.	71.70	24.25	7.00	52	10.05	3.05
32.	71.70	24.20	6.08	20	5.31	0.77
33.	71.75	24.50	8.02	21	5.55	2.47
34.	71.75	24.45	7.77	29	7.15	0.62
35.	71.75	24.40	7.51	52	10.05	2.54
36.	71.75	24.35	7.24	17	4.51	2.73
37.	71.75	24.30	7.00	45	9.33	2.33
38.	71.75	24.25	7.00	27	6.80	0.20
39.	71.75	24.20	5.00	26	6.61	1.61
40.	71.75	24.15	5.17	67	11.30	6.13
41.	71.75	24.10	5.04	25	6.42	1.34
42.	71.75	24.00	5.00	29	7.15	2.15
43.	71.80	24.50	8.65	25	6.42	2.25
44.	71.80	24.45	8.48	44	9.22	0.74
45.	71.80	24.40	8.28	32	7.64	0.64
46.	71.80	24.35	8.00	25	6.42	1.58
47.	71.80	24.30	9.25	37	8.36	0.89
48.	71.80	24.25	9.63	38	8.49	0.14
49.	71.80	24.20	9.00	49	9.75	0.75
50.	71.80	24.15	7.80	40	8.75	0.95
51.	71.80	24.05	7.48	38	8.49	1.01
52.	71.80	24.00	5.10	33	7.79	2.68
53.	71.85	24.05	9.24	50	9.85	0.61
54.	71.85	24.45	9.28	26	6.61	2.67
55.	71.85	24.40	9.16	28	6.98	2.18

Contd. Table – 4

Sl. No.	Longitude (Degrees)	Latitude (Degrees)	Inter – polated Depth, D (m.)	Reflect-ance	Predicted depth, P (m.)	Deviation x = ¦D–P¦ (m.)
56.	71.85	24.35	9.33	50	4.85	0.52
57.	71.85	24.30	11.57	38	8.49	3.08
58.	71.85	24.25	12.20	65	11.15	1.05
59.	71.85	24.15	12.50	70	11.52	0.98
60.	71.85	24.10	13.00	61	10.84	2.16
61.	71.85	24.05	7.00	35	8.09	1.09

Table – 5

Field data & calculations for prediction
(CCT method : Region (2), Gujrat)

Sl. No.	Longitude (Degrees)	Latitude (Degrees)	Inter – polated Depth, D (m.)	Reflect-ance	Predicted depth, P (m.)	Deviation x = ¦D–P¦ (m.)
1.	71.90	24.50	9.90	24	6.22	3.68
2.	71.90	24.45	10.14	23	6.00	4.14
3.	71.90	24.40	10.58	53	10.14	0.44
4.	71.90	24.35	11.77	32	7.64	4.13
5.	71.90	24.30	13.75	38	8.49	5.26
6.	71.90	24.25	14.76	25	7.42	8.34
7.	71.90	24.20	14.76	62	10.92	3.84
8.	71.90	24.15	14.80	76	11.93	2.87
9.	71.90	24.10	15.0	32	7.64	7.36
10.	71.90	24.05	11,40	61	10.84	0.56
11.	71.90	24.00	7.50	38	8.49	0.99
12.	71.95	24.50	10.53	29	7.15	3.38

Contd. Table - 5

Sl. No.	Longitude (Degrees)	Latitude (Degrees)	Inter - polated Depth, D (m.)	Reflect-ance	Predicted depth, P (m.)	Deviation x = |D-P| (m.)
13.	71.95	24.45	10.75	47	9.55	1.20
14.	71.95	24.40	12.33	31	7.48	4.85
15.	71.95	24.35	12.08	38	8.49	3.59
16.	71.95	24.30	14.27	18	4.79	9.48
17.	71.95	24.25	19.33	65	11.15	6.18
18.	71.95	24.20	17.33	22	5.78	9.10
19.	71.95	24.15	17.27	36	8.23	9.04
20.	71.95	24.10	14.50	59	10.67	3.85
21.	71.95	24.05	10.25	27	6.80	3.45
22.	71.95	24.00	10.20	62	10.92	0.72
23.	72.00	24.50	15.00	47	9.55	5.45
24.	72.00	24.45	13.00	26	6.61	6.39
25.	72.00	24.40	12.50	42	8.99	3.51
26.	72.00	24.35	14.20	17	4.51	9.69
27.	72.00	24.30	18.57	27	6.80	11.87
28.	72.00	24.25	19.70	14	16.16	12.83
29.	72.00	24.20	19.66	36	8.23	11.43
30.	72.00	24.15	17.67	64	11.10	6.56
31.	72.00	24.10	14.40	8	0.77	13.63
32.	72.00	24.05	10.50	45	9.33	1.17
33.	72.05	24.50	19.00	29	7.15	11.85
34.	72.05	24.45	19.00	27	6.80	12.30
35.	72.05	24.35	21.00	46	9.44	10.66
36.	72.05	24.30	22.00	26	6.61	15.39
37.	72.05	24.25	22.00	26	6.61	15.39
38.	72.05	24.01	17.00	13	3.18	13.82
39.	72.05	24.10	14.27	68	11.38	2.89
40.	72.10	24.40	19.00	26	6.61	12.39
41.	72.10	24.35	19.33	56	10.42	8.91
42.	72.10	24.30	20.67	27	6.80	13.97
43.	72.10	24.25	22.61	36	8.23	14.39

Contd... Table - 5

Sl. No.	Longitude (Degrees)	Latitude (Degrees)	Inter - polated Depth, D (m.)	Reflect - ance	Predicted depth, P (m.)	Deviation x = D - P (m.)
44.	72.10	24.15	16.78	76	11.93	4.86
45.	72.10	24.10	14.67	26	6,61	8.06
46.	72.15	24.35	19.00	23	6.00	13.00
47.	72.15	24.30	19.40	49	9.75	9.65
48.	72.15	24.25	19.90	22	5.78	14.12
49.	72.15	24.20	18.75	26	6.61	12.14
50.	72.15	24.15	16.05	50	9.85	6.19
51.	72.15	24.10	14.53	36	8.23	6.31
52.	72.20	24.30	19.00	19	5.06	13.94
53.	72.20	24.25	19.00	53	10.14	8.86
54.	72.20	24.00	18.33	66	11.23	7.10
55.	72.20	24.15	16.14	35	8.09	6.29
56.	72.20	24.10	14.11	66	11.23	2.88
57.	72.25	24.25	17.50	53	10.14	7.36
58.	72.25	24.20	18.23	34	7.94	10.29
59.	72.25	24.15	15.95	47	8.36	7.59
60.	72.30	24.25	13.00	23	6.00	7.00
61.	72.30	24.20	16.11	59	10.67	5.44

Table - 6

Field data & calculations for prediction
(CCT method : Region (3), Gujrat)

Sl. No.	Longitude (Degrees)	Latitude (Degrees)	Inter - polated Depth, D (m.)	Reflect - ance	Predicted depth, P (m.)	Deviation x = D - P (m.)
1.	72.35	24.25	7.57	44	9.22	1.65
2.	72.35	24.20	10.17	20	5.31	4.86
3.	72.40	24.25	5.00	59	10.67	5.67
4.	72.40	24.20	5.00	29	7.15	2.15
5.	72.45	24.15	9.80	26	6.61	3.19
6.	72.50	24.15	9.00	50	9.85	0.85
7.	72.55	24.15	11.00	29	7.15	3.85
8.	72.60	24.15	11.00	28	6.98	4.20
9.	72.65	24.15	11.00	59	10.67	0.33
10.	72.70	24.15	11.00	19	5.06	5.94

Table – 7

Field data & calculations (CCT method :Gujrat region; for depths > 10 m.)

Sl. No.	Latitude (Degrees)	Longitude (Degrees)	Measured depth (m.)D	Line No.	Pixel No.	Reflectance	Predicted Depth(m)P	Deviation x= P–D; (m.)
1.	24.280	72.180	11.50	1679	1247	51	9.95	1.55
2.	24.220	72.020	12.20	1804	1040	48	9.65	2.55
3.	24.350	72.530	10.80	1495	1725	51	9.95	0.85
4 .	24.190	72.430	11.20	1755	1650	59	10.59	0.61
5.	23.875	72.635	12.00	2173	2089	48	9.65	2.35
6.	23.850	72.640	12.00	2209	2107	27	6.70	5.30
7.	23.825	72.645	12.00	2245	2125	17	4.51	6.49
8.	23.850	72.665	14.00	2203	2143	36	8.23	5.77
9.	23.825	72.675	14.00	2238	2169	24	6.22	7.78
10.	23.800	72.680	14.00	2274	2188	45	9.33	4.67
11.	23.850	72.690	16.00	2197	2180	33	7.79	8.21
12	23.825	72.698	16.00	2232	2203	33	7.79	8.21
13.	23.800	72.700	16.00	2269	2217	50	9.85	6.15
14.	23.825	72.727	18.00	2226	2245	55	10.33	7.67
15.	23.800	72.727	18.00	2262	2257	52	10.05	7.95
16.	23.772	72.737	20.00	2301	2284	59	10.67	9.33
17.	24.266	72.183	14.50	1698	1257	45	9.33	5.17
18.	24.174	72.458	10.80	1770	1698	35	8.09	2.71
19.	24.081	71.941	10.00	2027	986	26	6.61	3.39

CHAPTER - 3

MICRO DENSITOMETER METHOD

3.1 Micro Densitometer Approach:

3.1.1. General:

The micro-densitometer is an instrument which measures the light density at any point on the negative of a photo imagery. The Transmittivity, T, is defined as the ratio of the amount of light transmitted to the negative to the amount of light incident on the negative at any particular point on the negative. So 'T' can vary from '1' (transparent part of the negative) to '0' (Opaque part of the negative). Light Density, $D = \log_{10}(\frac{1}{T})$ --- (1).

Variations in surface features on land are reflected as variations in the shades or tones of a Black and White negative of an imagery. These variations in shades can be expressed in terms of variations in light density. Hence light density is an index of the properties of surface features mapped in an imagery. The microdensitometer gives a plot of transmittivity, T, versus distance along any straight line etc. on a photo - negative. The value of 'T' at any desired spot can be noted from this plot and the corresponding light density 'D' can be found out from equation (1).

3.1.2 Case Study:

Microdensitometer plots for this imagery were obtained from the Satellite Applications Centre, Ahmedabad (Gujrat). The photo negative was divided into six equi spaced lines such that three lines covered the Rajasthan region and the other three covered the Gujrat region.

Continuous Micro Densitometer plots for each of these lines were then obtained.

3.1.3 Calibration:Part:

A field study was undertaken to the Rajasthan and Gujrat regions and 50 wells were mapped and there water depths the latitudes and longitudes of the nearest land mark on the map noted, as well as the orientation and the distance to the landmark from each well. The corrected latitudes and longitudes of each well were then determined from the following relation:

α = Angle between the north direction and the line to the Actual location from the assumed location

d = distance

$$\text{Lat. corr. } \Delta\emptyset'' = \pm \frac{d \ \text{Cos}\alpha}{R_m} \times 206265$$
(in seconds)

R_m = 6378 Km. (mean radius of earth)

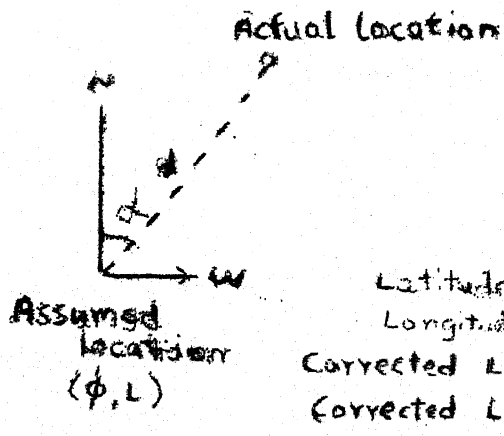
$$\text{Long. Corr., } \Delta L'' = \frac{d \ \text{Sin}\alpha}{R_m} \times 206265$$
(in seconds)

These mapped ground water well points were then located on a ground water board map of the region (scale 1" = 4 mile). Those points which feel on any of the six lines (for microdensitometer study) or in the near vicinity, were chosen for calibration. The light density at these chosen points were ascertained from the micro-densitometer plots, for the Gujrat region (lines 4, 5, 6). Only the Gujrat region was considered as the CCT study had earlier indicated a lack of appreciable correlation in the Rajasthan region (see Figs. 2-5). The four plots were made on ordinary (see fig. No.11-14) graph paper by plotting light density versus depth. The first three plots were for lines 4, 5, 6

Table – 8

Field data for Gujrat region
(Lines 4, 5, 6 : Densitometer method)

Sl. No.	LINE NO. 4		LINE NO. 5		LINE NO. 6	
	Density	Depth (m.)	Density	Depth (m.)	Density	Depth (m.)
1.	0.796	5.60	0.745	5.90	0.921	5.40
2.	0.699	6.50	0.639	6.50	0.903	5.50
3.	0.620	8.00	0.620	7.20	0.757	5.60
4.	0.629	8.60	0.678	7.80	0.796	5.70
5.	0.602	9.30	0.602	8.90	0.685	6.00
6.	0.620	10.00	0.585	9.20	0.678	6.30
7.	0.620	10.00	0.602	9.50	0.638	7.10
8.	0.620	10.00	0.620	8.50	0.648	7.60
9.	0.629	9.80	0.620	7.60	0.638	8.50
10.	0.620	9.40	0.658	6.90		
11.	0.638	9.00				
12.	0.678	7.70				



Latitude = ϕ
Longitude = L
Corrected Lat, $\phi' = \phi \pm \Delta\phi''$
Corrected Long, $L' = L \pm \Delta L''$

Fig. 10

Light Density vs. depth plot

Fig.11 Micro- Densitometer method (Line 5)

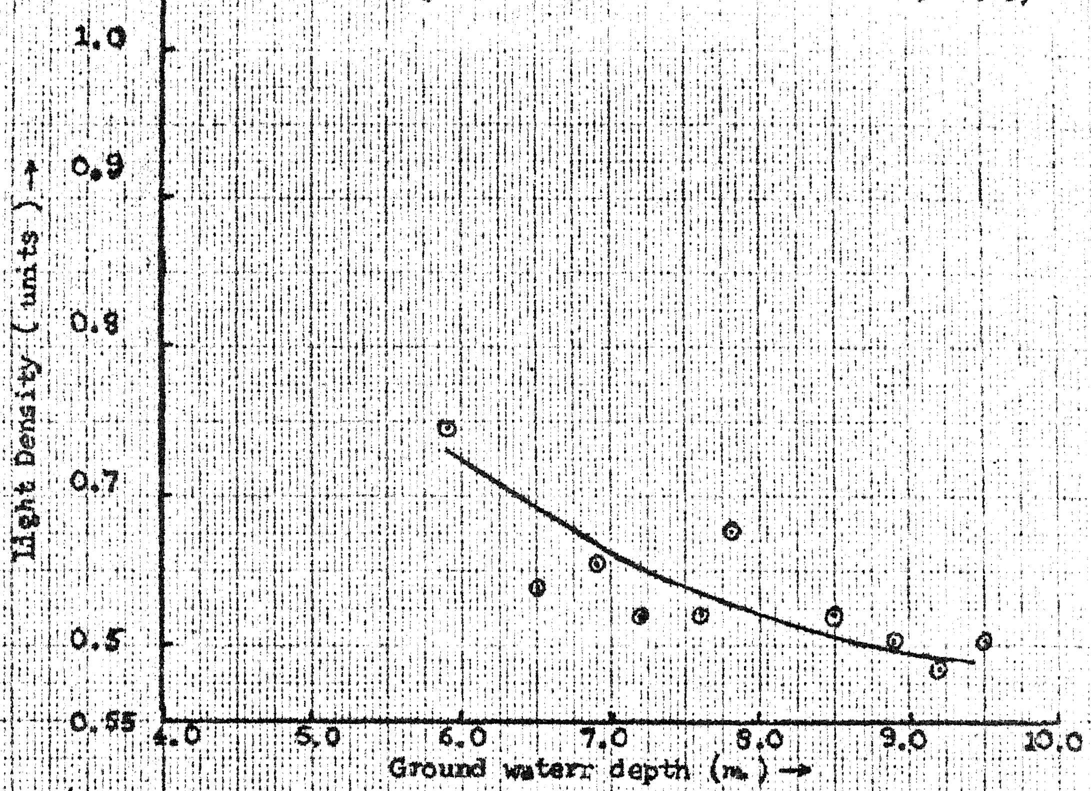
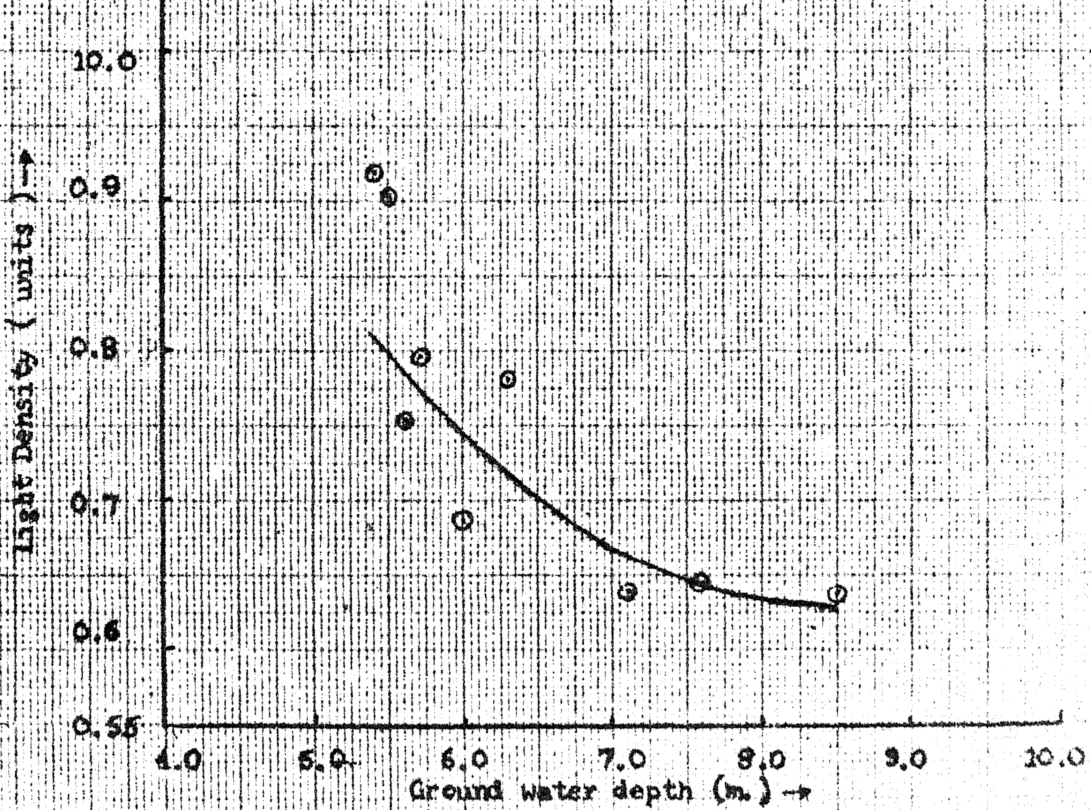


Fig.12 Micro- Densitometer method (Line 6)



Light Density vs. Depth plot

Fig.13 Micro- Densitometer method (Line 4)

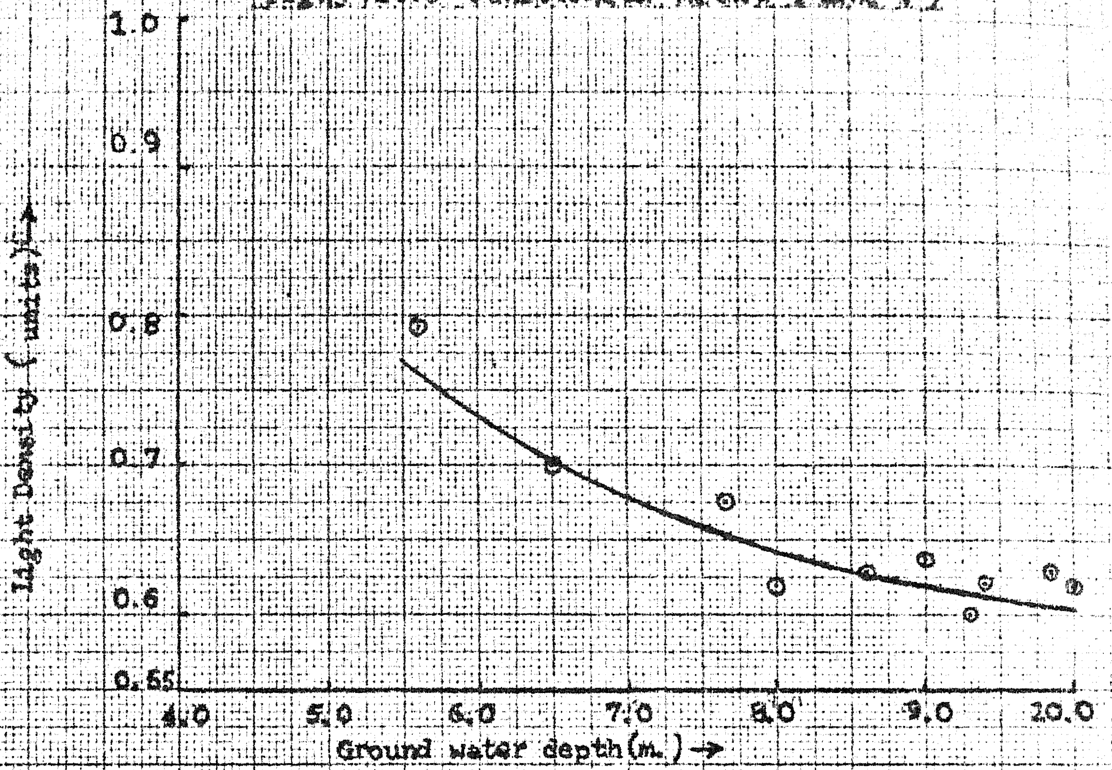
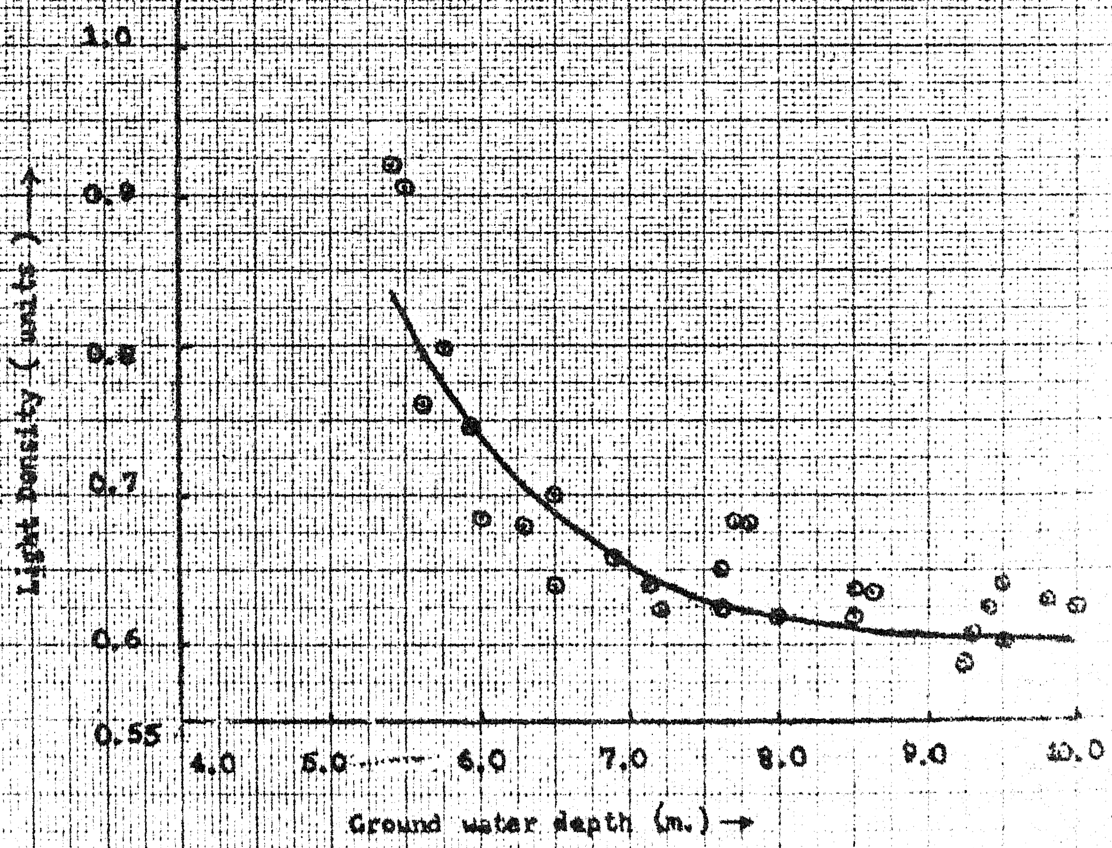


Fig.14 Micro- Densitometer method (Lines 4,5,6)
(Master plot)



individually and the fourth plot was for the combined data of lines 4, 5, 6. Each of these four graphs established that at water depths deeper than 10 m there is so much 'scatter' on each graph that it can be concluded that there is no appreciable correlation beyond this depth, between the light density (satellite reading) and the water depth. Each graph showed an exponentially decaying curve of this mathematical form: $y = e^{bx + c}$. The equation of each curve was established by finding the values of 'b' and 'c' for each curve by the method of least squares curve fitting. Please refer to(Appendix - III).

The calibration curves for lines 4, 5, 6 and combined plot for lines 4, 5, 6 (master plot) are given in Figs. 11-14 and the curve equations and correlations coefficient (see appendix 3, are given in table 9.

Table No. 9

Lines	Calibration Curve Equation B,C		Coefficient of Correlation
	B	[illegible]	r
4	- 0.04761652	- 0.02515450	- 0.88415922
5	- 0.04636945	- 0.09178096	- 0.78772666
6	- 0.10596548	+ 0.36929877	- 0.79501882
4, 5, 6 combined	- 0.05901143	+ 0.05047683	- 0.79258990

Calibration Curve equation, $y = e^{bx + c}$

3.1.4 Comments:

i) The negative values of the coefficients of correlation indicate that 'y' decreases with increase in 'x'.

ii) Possible explanation for the light density to decrease with water depth is an exponentially decaying curve may be

as follows: water does not reflect radiation in Band – 7, hence a surface water body such as a lake, in Band – 7 would theoritically appear opaque on a positive film (i.e., on a 'positive' negative). Its transmittivity, T, would be '0' and, therefore, its density, D, would be infinite according to Eq.(1). As the ground water depth increases, the effect of soil moisture decreases and the same soil shows greater reflectance and, therefore, a greater transmittivity on a positive film, and hence a decreasing density. Hence a micro-densitometer plot of any line on a positive film of a particular area, in our case the Gujrat region, would show a high density value at very shallow ground water depth, which decreases exponentially with increase in the depth.

iii) The high value of 'r' indicates an excellent correlation between the light density and the water depth upto 10 metres. The plots for lines 4, 5 6 can be treated as auxilliary curves or verification curves for checking the water depths given by the master plot of lines 4, 5 6, though the latter by itself has a very high coefficient of correlation (–0.793). (The surface area covered by the master plot is approximately 185 Km x 90 Km. of Gujrat region). (See Figs. 11 to 14.)

3.2 Prediction Part (Micro-densitometer approach):

Only the Gujrat region the given imagery was considered for the prediction part because the given Rajasthan region indicated no appreciable correlation during the calibration phase (see 'CCT method' page 9).

In the CCT prediction process the given Gujrat region was subdivided into Regions (1) (2) & (3) (see page 19). In the densitometer method the Region (2) & Region (3) (for lack of contour points in the given depth contour map) were combined as Region (2), & it was demonstrated that the satellite survey is not reliable for such regions (see'Results: densitometer method').

A number of points were taken on a 1" = 4 miles scale map of the Gujrat region supplied by the local ground water board authorities. This map had ground water contours plotted on it by conventional methods. Next each of these points were alloted to one of the three lines (lines 4, 5, 6) and the position of each point with respect to the corresponding line noted. Also the ground water depth at each point was recorded from this map, if necessary by interpolation.

Next the relevant line corresponding to each point on the map was considered and the corresponding light density value was noted from the microdensitometer plots. Then this density value was utilized to predict the corresponding ground water depth from the master calibration curve as well as from the auxillary calibration curve for each line. The ground water depth(s) so obtained were then checked by comparison with the depths obtained from the conventional ground waster contour map (see Fig. 15). This completed the prediction of the ground water depth for one point on the map. This prediction process was repeated for the other points taken on the map for ground water prediction. The mean errors

Table - 10

Field data and calculation for prediction :
(Gujrat region 1)

Sl. No.	Longitude (Degrees)	Latitude (Degrees)	Line No.	Density	Predicted depth line 456 (m.), P	Interpolated depth, D (m.)	Deviation x = |P - D| (m.)
REGION 1							
1.	71.014	24.543	4	0.638	8.47	9.00	0.53
2.	71.840	24.520	4	0.593	9.71	9.27	0.44
3.	71.864	24.518	4	0.602	9.46	9.54	0.08
4.	71.884	24.514	4	0.595	9.65	9.82	0.17
5.	71.542	24.291	5	0.678	7.45	5.00	2.45
6.	71.579	24.284	5	0.678	7.45	7.00	0.45
7.	71.626	24.277	5	0.638	8.47	7.00	1.47
8.	71.765	24.253	5	0.619	8.96	7.00	1.96
9.	71.777	24.295	5	0.602	9.45	9.00	0.45
10.	71.412	24.044	6	0.638	8.46	7.00	1.46
11.	71.444	24.042	6	0.619	8.96	9.00	0.04
12.	71.535	24.026	6	0.638	8.46	9.00	0.45
13.	71.602	24.014	6	0.745	5.84	7.00	1.26
14.	71.693	24.000	6	0.745	5.84	7.00	1.26
15.	71.793	23.984	6	0.553	10.90	5.00	5.90
16.	71.884	23.969	6	0.638	8.46	7.00	1.46
17.	71.479	24.040	6	0.699	6.92	8.00	1.08
18.	71.488	24.033	6	0.678	7.45	9.00	1.55
19.	71.576	24.019	6	0.854	3.53	8.00	4.47
20.	71.650	24.007	6	0.678	7.45	6.00	1.45
21.	71.743	23.991	6	0.699	6.92	5.00	0.08
22.	71.843	23.976	6	0.745	5.84	6.20	0.46
23.	71.600	24.014	6	0.769	5.31	7.00	1.69
24.	71.800	23.980	6	0.699	6.92	5.00	1.92

Table – 11

Field data calculations for prediction :
(Gujrat region 2)

Sl. No.	Longitude (Degrees)	Latitude (Degrees)	Line No.	Density	Predicted depth line 456 (m.)P	Inter – polated depth, D (m.)	Deviation x=|P–D| (m.)
REGION 2							
1.	72.000	24.512	4	0.678	7.54	15.00	7.46
2.	71.992	24.514	4	0.602	9.46	13.00	3.54
3.	71.983	24.517	4	0.600	9.51	11.00	1.49
4.	72.005	24.514	4	0.602	9.46	17.00	7.54
5.	72.011	24.512	4	0.638	8.47	19.00	10.53
6.	71.819	24.249	5	0.709	4.95	11.00	6.05
7.	71.851	24.239	5	0.658	7.96	13.00	5.04
8.	71.893	24.235	5	0.678	7.45	15.00	7.55
9.	71.954	24.228	5	0.678	7.45	17.00	9.55
10.	71.977	24.221	5	0.638	8.47	19.00	10.53
11.	72.093	24.200	5	0.638	8.47	19.00	10.53
12.	72.219	24.179	5	0.553	10.89	17.00	6.11
13.	72.263	24.172	5	0.769	5.29	17.00	11.71
14.	72.302	24.165	5	0.658	7.96	15.00	7.04
15.	72.321	24.184	5	0.658	7.96	13.00	5.04
16.	72.339	24.160	5	0.619	8.97	11.00	2.03
17.	72.358	24.158	5	0.678	7.45	9.00	1.55
18.	72.388	24.149	5	0.585	9.94	9.00	0.94
19.	72.430	24.147	5	0.585	9.94	11.00	1.06

and the standard errors were computed for Regions (1) and (2) to assess the accuracy of prediction in each region(see page 19).

Once it was established that this method provided a good accurac of prediction, the need of comparing with each predicted ground water depth with the conventional ground water contour map of an area is no longer necessary and the calibration prediction curves can be reliably used to predict (or update old conventional maps) shallow ground water depths in unmapped areas.

RESULTS AND DISCUSSION (MICRO-DENSITOMETER APPROACH):

Region(1) : (See table - 10)

Number of points N=24,

Standard error, $\sigma = 1.38$ m

The $3 - \sigma$ test showsthat we have to reject any $x > 4.14$ m hence we reject the two observations corresponding to serial nos 15 and 19 in table - 10. Therefore, we have :

$N = 22, \quad \sigma = \pm 0.71$ m

We get a good prediction accuracy, therefore, in Region (1) as the standard error is $\pm$ 1.00 m. Region (1) is mostly Alluvial with ground water depths less than 10 m, where our satellite survey methods are most effective.

Region (2) : (See table -11)

$N = 19, \sigma = 3.56$ m

The $3 - \sigma$ test shows that we have to reject any $x > 10.68$ m, hence one observation corresponding to serial no. 13 in table - 11 is discarded. Therefore, we get : $N = 18, \sigma = 3.39$ m.

The high value of the standard error indicate that the satellit survey methods are unreliable in Region(2), which is mostly hilly and with water depths greater than 10 m.

3.3 Sources of Error (CCT and Densitometer methods) :

1. The normal water level in some of the wells in the Gujrat region was lowered by 0.5 m. - 1.0 m. due to pumping operations, when the field data was collected. Hence the water levels in these wells represented a lesser values of the actual ground water depths.

2. Ideally, the satellite survey and the collection of field data (as well as preparing a conventional water depth contour map) should be done simultaneously. In practice, it is preferable to collect both types of data as close to each other as possible. Otherwise, the effect of seasonal variation of ground water depths comes into play, and the information recorded by a satellite and by a field observation, at any particular sport, will not indicate the same depth, but different depths due to seasonal variation. In this study, the satellite survey was done in June 1977, the field data was collected in December 1979 and February 1980, and the conventional water depth contour map was prepared in December, 1978. The correction due to seasonal variation could not be applied to the water depths due to lack of data. The low value of the standard error achieved (for ex.,+ 0.99 m. : CCT method), without correction due to the seasonal variation, indicates the high accuracy possible once the seasonal variation factor is taken into account.

3. To pin point the latitudes and longitudes, a 1" = 4 miles ground water contour map was used, for the CCT method. A higher accuracy could have been achieved with a larger scale map.

CHAPTER - 4

DISCUSSION, CONCLUSION AND RECOMMENDATIONS

4.1 DISCUSSION, CONCLUSION AND RECOMMENDATIONS:

How well can ground water depth be estimated from satellite data?

For the given Rajasthan region, the application of the CCT method yielded no appreciable correlation between the ground water depth and the satellite data, using the central pixel method and the linear averaging method (3, 5 7 pixels array). This indicated that we can not reliably estimate water depths from satellite datain this region, which is mostly sandy and with water depths in excessof 10 m . The hilly terrain in the lower Rajasthan region, i.e. Mount Abu hills, were not included in this study because these prediction methods are not reliable in hilly areas.

Next we studied the Gujrat region given in the imagery with the help of the CCT method and the micro-densitometer method. Three different types of (for Regions (1), (2), (3), see page 19) were classified depending upon terrain (alluvial or hilly) and water depth (greater than or less than 10 m). The calibraion prediction yielded very promising prediction accuracy (standard error=0.99 m). in case of CCT method andstandard error 0.71 m in case of densitometer method) (see pages 20, 40) in Region (1), where the terrain was mostly alluvial with water depths less than 10 m. It wasin this type of region that we had the best results. On the other hand, as anticipated, both methods yielded poor results (see pages 21, 40) for Regions (2) and (3), where the terrain was mostly hilly and water depths greater than 10 m.

A study of field data (see p. 29) in the Gujrat region, of depths greater than 10 m, established that the CCT method yields a poor accuracy (standard error = 2.63 m, see p.20).

Thus we can conclude that both the CCT method and the micro-densitometer method are best applied to alluvial soil with shallow water depths not exceeding 10 m. A few points of interest are discussed here.

<u>CCT Method Vis-a-vis the Micro-densitometer Method</u> :

For the given Gujrat region, the correlation coefficients and the standard errors - 0.939 m and 0.99 m (Region (1)) iscase of the CCT method, and -0.793 m and 0.71 m. in case of micro-densitometer approach. It was found that ground water depths deeper than 10.0 m cannot be estimated because of a lack of correlation with the satellite data. Two points are to be noted. First isthat the above values of the correlation coefficients (0.8 - 0.9) indicate a strong correlation and the second point is that its value is higher for the CCT approach. (The correlation coefficients varies from-1) to +1 and the closer to unity it is, the stronger the correlation.)
A correlation coefficient of 0-0.5 (test at 5% level of confidence) indicates no correlation to a negligibly small correlation while 0.7 - 1.0 indicate a good to an excellent correlation). Again the standard errors are very reasonable considering the sources of errors (see 'Sources of error'). The fact that depths could be predicted to a metre (CCT approach), pointsto the higher degree of precision possible with the minimization and removal of these sources of errors.The standard error is lesser for the CCT approach.
The reason for this is that in CCT method, we have for more data

available (collected in lines and pixels) about every 80 m we have a reflectance reading - while in the microdensitometer method such precision was not available in the calibration part stage. The CCT approach is superior because it offers an enormously large wealth of data (1 line about a 185 Km) contains 2656 pixels, each pixel about 80 m square). The next LANDSAT has a resolution of about 30 m and a French land use satellite is being planned for a resolution of 10 to 20 m. ~~with these.~~ With these satellites, the CCT method will offer an even more accurate picture of the ground water profile and an accuracy of within half a metre in areas conductive to satellite survey can be realized. This is not to belittle the microdensitometer method, which by itself is good enough to give good estimates but only that a higher precision can be obtained with the CCT method.

Central pixel method vis-a-vis the Grid averaging methods (CCT approach):

In the CCT method, in the study of Gujrat region, the correlation coefficient decreases from the central pixel method to 0.55 for the 7 pixels Grid pixel method and hence the degree of accuracy gets lesser. The reason for this trend is that we are assuming the ground water depth (which remains constant over a limited area only) to remains at a constant level over an increasing area as we move from the central pixel method to the 3 pixels, 5 pixels and 7 pixels Grid averaging. The precision therefore decreases. In the 7 pixels land case, the correlation coefficient is only 0.55, indicating a very poor correlation. Thismeans that the ground water depths should not be averaged beyond a ground surface distance of about 400 m allowed

the 5 pixels grid method (each pixel $\approx$ 80 m, length of a 5 pixels grid $\approx$ 5x80 = 400m). Otherwise there will result a negligibly small correlation or no correlation as in case of a 7 pixel grid averaging of the Gujrat area. Also it means that the central pixel method is most accurate in the CCT approach. The restriction of 400 m. on the grid averaging also means that a remote sensing satellite should have atleast a pixel resolution of 400 m to map shallow ground water depths. The first Indian Remote Sensing Satellite, Bhaskara - 1, has a pixel resolution much larger hence lacks the precision required. It is hoped that with the Indian Space Research program maintaining its ambitious program, ISRO will in a not too distant future put a Bhaskara series satellite of pixel resolution well below 100 m. When this happens, indigeneous satellite survey based on the CCT and microdensitometer methods explained in this study will be realized. Till we achieve the required pixel resolution in our very own Bhaskara etc., ISRO can procure LANDSAT data to develop a satellite ground water depth contour map of most parts of India.

Satellite Survey vis-a-vis Aircraft Survey:

Aircraft Survey:Versus Satellite Survey

The objective of ground water depth prediction can be achieved using both an aircraft and the satellite with MSS equipment. But the advantage of a satellite is the larger area coverage (185 Km x 185 Km: LANDSAT) compared to an aircraft. A satellite survey more suitable in a ground water depth estimation in large areas, which would require a large number of flights (and camera exposures) by aircraft. Aircraft survey is suited for covering small local areas or for those projects where steroscopic photographs are needed.

It is obvious that to prepare ground water maps of large areas, the superior option is a salellite borne survey.

Summing it up, this study has proved that it is possible to predict shallow ground water depths from remote sensing satellites with a good accuracy. Ground water depths upto 10 m. depth can be estimated while rocky areas or built up areas or areas under dense forest cover etc. cannot be covered by a satellite surveys. The given Gujrat region was probed with two techniques, one using CCTs and the other a micro-densitometer. Upto 10 m. depths could be estimated with a high correlation and very reasonable standared errors especially when quite a few sources of error existed. Undoubtably the standard error of ± 0.99 m.(CCT approach) can be refined considerably with the removal of these sources of error. The highly encouraging results obtained in this project highlight the tremendous scope of predicting shallow ground water depths by satellite surveys.

** **

APPENDIX - 1.

```
C     THIS PROGRAM CONVERTS THE LATITUDE AND LONGITUDE OF A POINT ON THE
C     GROUND TO ITS CORRESPONDING LINE-NUMBER AND PIXEL NUMBER ON THE
C     IMAGERY AFTER CORRECTING FOR THE CURVATURE OF THE EARTH.

      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      DIMENSION PL(200),PPHI(200),XP(200),YP(200),U(200),V(200)
     9,QPHI(200)
      OPEN(UNIT=7,DEVICE='DSK')
      READ(7,*)N
      READ (7,*)(PL(I),PPHI(I),I=1,N)
100   FORMAT(I4)
200   FORMAT(2F11.6)
      DO 905 I=1,N
      QPHI(I)=PPHI(I)*3.141593/180.
      CALL VAL(RPHI,R,OPHI,OL,RM,RN)
      DL=PL(I)-OL
      DPHI=QPHI(I)-OPHI
      C=DL*(SIN(OPHI))
      SM=RM*(QPHI(I)-OPHI)
      DM11=SM**3
      DM12=6*(R**2)
      DM1=DM11/DM12
      DM211=SM**4
      DM212=SIN(OPHI)/COS(OPHI)
      DM22=24*(R**3)
      DM2=DM211*DM212/DM22
      DM=SM+DM1-DM2
      RPDM=RPHI-DM
      C=C*3.141593/180
      SIC=SIN(C)
      XP(I)=RPDM*SIC
      YP(I)=RPHI-(RPHI-DM)*COS(C)
      TYPE*,XP(I),YP(I)
      A1=-00.00214750
      B1=-0.01331120
      C1=3839.33110000
      D1=0.01437828
      E1=-0.00382949
      F1=72.19580300
      U(I)=A1*XP(I)+B1*YP(I)+C1
      V(I)=D1*XP(I)+E1*YP(I)+F1
      PRINT1000,I,PL(I),PPHI(I),U(I),V(I)
1000  FORMAT(1X,I4,1X,' LONGITUDE= ',F11.6,' LATITUDE= ',F11.6,
     9' LINE NUMBER= ',F6.0,' PIXEL NUMBER= ',F6.0)
905   CONTINUE
      STOP
      END
      SUBROUTINE VAL(RPHI,R,OPHI,OL,RM,RN)
      F=6.37730124
      G=10**6
      A=F*G
      E=1/300.8
      OPHI=23.*3.141593/180.
      H=E**2
      S=SIN(OPHI)
      S2=S**2
      B=SQRT(1-H*S2)
      RN=A/B
      D=B**3
      UN=A*(1.-H)
      RM=UN/D
      R=SQRT(RN*RM)
      RPHI=R*(COS(OPHI)/SIN(OPHI))
      OL=71.
      RETURN
      END
```

APPENDIX - 2.

```
C     PROGRAM TO READ THE REFLECTANCE VALUES IN BINARY FORM FROM THE
C     TAPE AND THEN TO CONVERT THEM TO THEIR DECIMAL VALUES.
      INTEGER BT1,BT2,BT3,BT4,BT5
      DIMENSION IA(840),LAST(30),VL(30)
      OPEN(UNIT=20,DEVICE='MTA0',MODE='DUMP'
     9,RECORD SIZE=840,DENSITY='800')
      OPEN(UNIT=21,FILE='FOR21.DAT')
      DATA IB/5H     /
      DATA LAST/30*999/
      ACCEPT*,MMM,M
61    FORMAT(5X,' THE LINE NUMBER OF THIS RECORD IS',I5)
      PRINT 61,MMM
      NI=M+12
      KAT=0
      K=0
      NREC=0
99    DO55N=1,840
55    IA(N)=IB
      READ(20)IA
      NO=-3
      K=K+1
      IF(K.GT.1)GO TO 90
221   I=0
222   I=I+1
      KC=0
      IF(IA(I).EQ.IB)GO TO 88
      IF(IA(I).GE.0)GO TO 25
      IA(I)=IA(I).AND."377777777777
      KC=1
25    BT1=IA(I)/2**28
      BT2=(IA(I)-BT1*2**28)/2**20
      BT3=(IA(I)-BT1*2**28-BT2*2**20)/2**12
      BT4=(IA(I)-BT1*2**28-BT2*2**20-BT3*2**12)/2**4
      BT5=(IA(I)-BT1*2**28-BT2*2**20-BT3*2**12-BT4*2**4)
      IF(BT5.GT.7)BT5=-(BT5-8)
      IF(KC.EQ.1)BT1=BT1+128
      NO=NO+4
      IF(M.GE.NI) GO TO 222
      IF(NO.NE.M)GO TO 222
      WRITE(21,500)NO,BT1,BT2,BT3,BT4,BT5
500   FORMAT(6I5)
      M=M+4
112   GO TO 222
88    WRITE(21,500)LAST
      CLOSE(UNIT=21)
777   KAT=KAT+1
      JKAT=KAT+5
      READ(21,500,END=888)(VL(I8),I8=KAT,JKAT)
      KAT=JKAT
      IF(KAT.LT.30)GO TO 777
      KAT=0
111   PRINT444,VL
444   FORMAT(3X,30I4)
      GO TO 777
888   KAT=0
      CLOSE(UNIT=21)
      NREC=NREC+1
      TYPE666,NREC
      GO TO 99
90    CLOSE(UNIT=20,DEVICE='MTA0',MODE='DUMP'
     9,RECORD SIZE=840,DENSITY='800')
666   FORMAT(' NO OF RECORDS READ= ',I5)
      STOP
      END
```

APPENDIX - 3.

```
C PROGRAM TO FIND CURVE EQUATION
      DIMENSION X(80),Y(80),A(80)
      NUN=0
      M=1
      N=75
      READ(21,*)(X(I),I=1,N),(Y(J),J=1,N)
      PRINT 44,N
44    FORMAT(15X,'INPUT DATA FOR CALIBRATION-PREDICTION CURVES',
     75X,'N=',I2)
      DO 42 I=1,75
      PRINT 770,X(I),Y(I)
770   FORMAT(10X,'X(I)=',F15.8,5X,'Y(I)=',F15.8)
42    CONTINUE
      N=N-44
5     CONTINUE
      C=0.0
      ANF=N-M+1
      DO 1 I=M,N
      Z=Y(I)
      A(I)=ALOG(Z)
      C=C+A(I)
1     CONTINUE
      D=0.0
      TA=0.0
      B=0.0
      DO 2 J=M,N
      S=A(J)
      W=X(J)
      DD=S*W
      D=D+DD
      B=B+W
      AA=W*W
      TA=TA+AA
2     CONTINUE
      IF(NUN.GE.4)GOTO 111
      MUN=NUN+3
      IF(MUN.LE.3)MUN=457
      PRINT 400,MUN
400   FORMAT(////,10X,'MICRO-DENSITOMETER METHOD',10X,
     4'LINE NUMBER(S)=',I2)
      GO TO 10
111   CONTINUE
      NIM=NUN-5
      LIM=NIM+2
      PRINT 401,LIM
401   FORMAT(////,10X,'MAGNETIC TAPE METHOD',10X,'NUMBER OF
     5 PIXEL(S)=',I2)
10    CONTINUE
      BB=(B*C-ANF*D)/(B**2-TA*ANF)
      CC=(B*D-TA*C)/(B**2-TA*ANF)
      PRINT100,BB,CC,NUN
100   FORMAT(///,5X,'BB=',F15.8,2X,'CC=',F15.8,2X,'NUN=',I2)
      DO 3 I=M,N
      T=BB*X(I)+CC
      XX=(A(I)-CC)/BB
      XDIF=X(I)-XX
      YY=EXP(T)
      YDIF=Y(I)-YY
      PRINT 200,X(I),XX,XDIF,Y(I),YY,YDIF
200   FORMAT(/,10X,'X(I)=',F10.4,3X,'XX=',F10.4,3X,'XDIF=',F10.4,3X,
     1'Y(I)=',F10.4,3X,'YY=',F10.4,3X,'YDIF=',F10.4)
3     CONTINUE
      CS=0.0
      DO 110 I=M,N
      CS=CS+A(I)
110   CONTINUE
      J=N-M+1
      AVX=B/J
      AVY=CS/J
```

```
      PRINT 700,AVX,AVY,NUN
700   FORMAT(//,5X,'AVX=',F15.8,2X,'AVY=',F15.8,2X,'NUN=',I2)
      ZSUM=0.0
      XSUM=0.0
      YSUM=0.0
      DO 50 I=M,N
      Q=X(I)-AVX
      R=Q**2
      S=A(I)-AVY
      V=S**2
      AQ=Q*S
      PRINT 500,X(I),Y(I),R,S,AQ
500   FORMAT(/,5X,'X(I)=',F10.4,2X,'Y(I)=',F6.3,2X,'RX=',F15.8,
     42X,'SY=',F15.8,2X,'AQXY=',F15.8)
      XSUM=XSUM+R
      YSUM=YSUM+V
      ZSUM=ZSUM+AQ
50    CONTINUE
      IF(J.LT.30)J=J-1
      AX=XSUM/J
      AY=YSUM/J
      XXSTD=SQRT(AX)
      YYSTD=SQRT(AY)
      TT=XSUM*YSUM
      SS=SQRT(TT)
      CORR=ZSUM/SS
      PRINT 600,XXSTD,YYSTD,CORR,J,XSUM,YSUM,ZSUM
600   FORMAT(//,5X,'X(I)STD=',F6.3,2X,'Y(I)STD=',F6.3,2X,
     7'CORRELATION COEFFICIENT=',F15.8,/,10X,'J=',I2,2X,'XSUM=',
     8F15.8,2X,'YSUM=',F15.8,2X,'ZSUM=',F15.8)
      NUN=NUN+1
      GO TO (6,7,8,11,12,13,14,15),NUN
6     CONTINUE
      M=1
      N=12
      GO TO 5
7     CONTINUE
      M=13
      N=22
      GO TO 5
8     CONTINUE
      M=23
      N=31
      GO TO 5
11    CONTINUE
      M=32
      N=42
      GO TO 5
12    CONTINUE
      M=43
      N=53
      GO TO 5
13    CONTINUE
      M=54
      N=64
      GO TO 5
14    CONTINUE
      M=65
      N=75
      GO TO 5
15    CONTINUE
      STOP
      END
```

APPENDIX - 4.

INPUT DATA N= 67

X(I)=	5.60000000	Y(I)=	0.79600000
X(I)=	6.50000000	Y(I)=	0.69900000
X(I)=	8.00000000	Y(I)=	0.62000000
X(I)=	8.60000000	Y(I)=	0.62900000
X(I)=	9.30000000	Y(I)=	0.60200000
X(I)=	10.00000000	Y(I)=	0.62000000
X(I)=	10.00000000	Y(I)=	0.62000000
X(I)=	10.00000000	Y(I)=	0.62000000
X(I)=	9.80000000	Y(I)=	0.62900000
X(I)=	9.40000000	Y(I)=	0.62000000
X(I)=	9.00000000	Y(I)=	0.63800000
X(I)=	7.70000000	Y(I)=	0.67800000
X(I)=	5.90000000	Y(I)=	0.74500000
X(I)=	6.50000000	Y(I)=	0.63900000
X(I)=	7.20000000	Y(I)=	0.62000000
X(I)=	7.80000000	Y(I)=	0.67800000
X(I)=	8.90000000	Y(I)=	0.60200000
X(I)=	9.20000000	Y(I)=	0.58500000
X(I)=	9.50000000	Y(I)=	0.60200000
X(I)=	8.50000000	Y(I)=	0.62000000
X(I)=	7.60000000	Y(I)=	0.62000000
X(I)=	6.90000000	Y(I)=	0.65800000
X(I)=	5.40000000	Y(I)=	0.92100000
X(I)=	5.50000000	Y(I)=	0.90300000
X(I)=	5.60000000	Y(I)=	0.75700000
X(I)=	5.70000000	Y(I)=	0.79600000
X(I)=	6.00000000	Y(I)=	0.68500000
X(I)=	6.30000000	Y(I)=	0.67800000
X(I)=	7.10000000	Y(I)=	0.63800000
X(I)=	7.60000000	Y(I)=	0.64800000
X(I)=	8.50000000	Y(I)=	0.63800000
X(I)=	9.90000000	Y(I)=	58.00000000
X(I)=	4.80000000	Y(I)=	19.00000000
X(I)=	6.80000000	Y(I)=	27.00000000
X(I)=	5.00000000	Y(I)=	19.00000000
X(I)=	5.80000000	Y(I)=	21.00000000
X(I)=	7.70000000	Y(I)=	24.00000000
X(I)=	5.40000000	Y(I)=	24.00000000
X(I)=	10.00000000	Y(I)=	59.00000000
X(I)=	8.70000000	Y(I)=	34.00000000
X(I)=	9.90000000	Y(I)=	59.00000000
X(I)=	4.80000000	Y(I)=	22.00000000
X(I)=	6.80000000	Y(I)=	26.00000000
X(I)=	5.00000000	Y(I)=	27.00000000
X(I)=	5.80000000	Y(I)=	24.00000000
X(I)=	7.70000000	Y(I)=	39.00000000
X(I)=	5.40000000	Y(I)=	37.00000000
X(I)=	10.00000000	Y(I)=	57.00000000
X(I)=	8.70000000	Y(I)=	43.00000000
X(I)=	9.90000000	Y(I)=	47.00000000
X(I)=	4.80000000	Y(I)=	30.00000000
X(I)=	6.80000000	Y(I)=	32.00000000
X(I)=	5.00000000	Y(I)=	31.00000000
X(I)=	5.80000000	Y(I)=	31.00000000
X(I)=	7.70000000	Y(I)=	41.00000000
X(I)=	5.40000000	Y(I)=	40.00000000
X(I)=	10.00000000	Y(I)=	45.00000000
X(I)=	8.70000000	Y(I)=	42.00000000
X(I)=	9.90000000	Y(I)=	43.00000000
X(I)=	4.80000000	Y(I)=	36.00000000
X(I)=	6.80000000	Y(I)=	39.00000000
X(I)=	5.00000000	Y(I)=	35.00000000
X(I)=	5.80000000	Y(I)=	35.00000000
X(I)=	7.70000000	Y(I)=	45.00000000
X(I)=	5.40000000	Y(I)=	47.00000000
X(I)=	10.00000000	Y(I)=	42.00000000
X(I)=	8.70000000	Y(I)=	48.00000000

MICRO-DENSITOMETER METHOD   LINE NUMBER(S)=457

BB= -0.05901143 CC= 0.05047683 NUN= 0

X(I)=	5.6000	XX=	4.7217	XDIF=	0.8783
Y(I)=	0.7960	YY=	0.7558	YDIF=	0.0402
X(I)=	6.5000	XX=	6.9238	XDIF=	-0.4238
Y(I)=	0.6990	YY=	0.7167	YDIF=	-0.0177
X(I)=	8.0000	XX=	8.9561	XDIF=	-0.9561
Y(I)=	0.6200	YY=	0.6560	YDIF=	-0.0360
X(I)=	8.6000	XX=	8.7119	XDIF=	-0.1119
Y(I)=	0.6290	YY=	0.6332	YDIF=	-0.0042
X(I)=	9.3000	XX=	9.4554	XDIF=	-0.1554
Y(I)=	0.6020	YY=	0.6075	YDIF=	-0.0055
X(I)=	10.0000	XX=	8.9561	XDIF=	1.0439
Y(I)=	0.6200	YY=	0.5830	YDIF=	0.0370
X(I)=	10.0000	XX=	8.9561	XDIF=	1.0439
Y(I)=	0.6200	YY=	0.5830	YDIF=	0.0370
X(I)=	10.0000	XX=	8.9561	XDIF=	1.0439
Y(I)=	0.6200	YY=	0.5830	YDIF=	0.0370
X(I)=	9.8000	XX=	8.7119	XDIF=	1.0881
Y(I)=	0.6290	YY=	0.5899	YDIF=	0.0391
X(I)=	9.4000	XX=	8.9561	XDIF=	0.4439
Y(I)=	0.6200	YY=	0.6040	YDIF=	0.0160
X(I)=	9.0000	XX=	8.4711	XDIF=	0.5289
Y(I)=	0.6380	YY=	0.6184	YDIF=	0.0196
X(I)=	7.7000	XX=	7.4407	XDIF=	0.2593
Y(I)=	0.6780	YY=	0.6677	YDIF=	0.0103
X(I)=	5.9000	XX=	5.8437	XDIF=	0.0563
Y(I)=	0.7450	YY=	0.7425	YDIF=	0.0025
X(I)=	6.5000	XX=	8.4446	XDIF=	-1.9446
Y(I)=	0.6390	YY=	0.7167	YDIF=	-0.0777
X(I)=	7.2000	XX=	8.9561	XDIF=	-1.7561
Y(I)=	0.6200	YY=	0.6877	YDIF=	-0.0677
X(I)=	7.8000	XX=	7.4407	XDIF=	0.3593
Y(I)=	0.6780	YY=	0.6638	YDIF=	0.0142
X(I)=	8.9000	XX=	9.4554	XDIF=	-0.5554
Y(I)=	0.6020	YY=	0.6221	YDIF=	-0.0201
X(I)=	9.2000	XX=	9.9408	XDIF=	-0.7408

```
Y(I)=   0.5850   YY=   0.6111   YDIF=   -0.0261
X(I)=   9.5000   XX=   9.4554   XDIF=    0.0446
Y(I)=   0.6020   YY=   0.6004   YDIF=    0.0016
X(I)=   8.5000   XX=   8.9561   XDIF=   -0.4561
Y(I)=   0.6200   YY=   0.6369   YDIF=   -0.0169
X(I)=   7.6000   XX=   8.9561   XDIF=   -1.3561
Y(I)=   0.6200   YY=   0.6717   YDIF=   -0.0517
X(I)=   6.9000   XX=   7.9481   XDIF=   -1.0481
Y(I)=   0.6580   YY=   0.7000   YDIF=   -0.0420
X(I)=   5.4000   XX=   2.2499   XDIF=    3.1501
Y(I)=   0.9210   YY=   0.7648   YDIF=    0.1562
X(I)=   5.5000   XX=   2.5844   XDIF=    2.9156
Y(I)=   0.9030   YY=   0.7603   YDIF=    0.1427
X(I)=   5.6000   XX=   5.5730   XDIF=    0.0270
Y(I)=   0.7570   YY=   0.7558   YDIF=    0.0012
X(I)=   5.7000   XX=   4.7217   XDIF=    0.9783
Y(I)=   0.7960   YY=   0.7513   YDIF=    0.0447
X(I)=   6.0000   XX=   7.2666   XDIF=   -1.2666
Y(I)=   0.6850   YY=   0.7382   YDIF=   -0.0532
X(I)=   6.3000   XX=   7.4407   XDIF=   -1.1407
Y(I)=   0.6780   YY=   0.7252   YDIF=   -0.0472
X(I)=   7.1000   XX=   8.4711   XDIF=   -1.3711
Y(I)=   0.6380   YY=   0.6918   YDIF=   -0.0538
X(I)=   7.6000   XX=   8.2076   XDIF=   -0.6076
Y(I)=   0.6480   YY=   0.6717   YDIF=   -0.0237
X(I)=   8.5000   XX=   8.4711   XDIF=    0.0289
Y(I)=   0.6380   YY=   0.6369   YDIF=    0.0011

    XSTAN. DEV.= 1.521  YSTAN. DEV.= 0.113
 CORRELATION COEFFICIENT=    -0.79258990


 MICRO-DENSITOMETER METHOD              LINE NUMBER(S)=  4


BB=    -0.04761652  CC=     -0.02515450  NUN= 1
X(I)=   5.6000   XX=   4.2633   XDIF=    1.3367
Y(I)=   0.7960   YY=   0.7469   YDIF=    0.0491
X(I)=   6.5000   XX=   6.9923   XDIF=   -0.4923
Y(I)=   0.6990   YY=   0.7156   YDIF=   -0.0166
X(I)=   8.0000   XX=   9.5110   XDIF=   -1.5110
```

```
Y(I)=     0.6200    YY=     0.6663   YDIF=   -0.0463
X(I)=     8.6000    XX=     9.2083   XDIF=   -0.6083
Y(I)=     0.6290    YY=     0.6475   YDIF=   -0.0185
X(I)=     9.3000    XX=    10.1297   XDIF=   -0.8297
Y(I)=     0.6020    YY=     0.6263   YDIF=   -0.0243
X(I)=    10.0000    XX=     9.5110   XDIF=    0.4890
Y(I)=     0.6200    YY=     0.6057   YDIF=    0.0143
X(I)=    10.0000    XX=     9.5110   XDIF=    0.4890
Y(I)=     0.6200    YY=     0.6057   YDIF=    0.0143
X(I)=    10.0000    XX=     9.5110   XDIF=    0.4890
Y(I)=     0.6200    YY=     0.6057   YDIF=    0.0143
X(I)=     9.8000    XX=     9.2083   XDIF=    0.5917
Y(I)=     0.6290    YY=     0.6115   YDIF=    0.0175
X(I)=     9.4000    XX=     9.5110   XDIF=   -0.1110
Y(I)=     0.6200    YY=     0.6233   YDIF=   -0.0033
X(I)=     9.0000    XX=     8.9100   XDIF=    0.0900
Y(I)=     0.6380    YY=     0.6353   YDIF=    0.0027
X(I)=     7.7000    XX=     7.6329   XDIF=    0.0671
Y(I)=     0.6780    YY=     0.6758   YDIF=    0.0022

     XSTAN. DEV.= 1.451  YSTAN. DEV.= 0.078
 CORRELATION COEFFICIENT=     -0.88415922


    MICRO-DENSITOMETER METHOD            LINE NUMBER(S)=  5


BB=    -0.04636945  CC=    -0.09178096  NUN= 2
X(I)=     5.9000    XX=     4.3690   XDIF=    1.5310
Y(I)=     0.7450    YY=     0.6939   YDIF=    0.0511
X(I)=     6.5000    XX=     7.6790   XDIF=   -1.1790
Y(I)=     0.6390    YY=     0.6749   YDIF=   -0.0359
X(I)=     7.2000    XX=     8.3299   XDIF=   -1.1299
Y(I)=     0.6200    YY=     0.6534   YDIF=   -0.0334
X(I)=     7.8000    XX=     6.4013   XDIF=    1.3987
Y(I)=     0.6780    YY=     0.6354   YDIF=    0.0426
X(I)=     8.9000    XX=     8.9653   XDIF=   -0.0653
Y(I)=     0.6020    YY=     0.6038   YDIF=   -0.0018
Y(I)=     9.2000    XX=     9.5831   XDIF=   -0.3831
Y(I)=     0.5850    YY=     0.5955   YDIF=   -0.0105
```

```
X(I)=     9.5000    XX=     8.9653    XDIF=     0.5347
Y(I)=     0.6020    YY=     0.5873    YDIF=     0.0147
X(I)=     8.5000    XX=     8.3299    XDIF=     0.1701
Y(I)=     0.6200    YY=     0.6151    YDIF=     0.0049
X(I)=     7.6000    XX=     8.3299    XDIF=    -0.7299
Y(I)=     0.6200    YY=     0.6413    YDIF=    -0.0213
X(I)=     6.9000    XX=     7.0471    XDIF=    -0.1471
Y(I)=     0.6580    YY=     0.6625    YDIF=    -0.0045

      XSTAN. DEV.= 1.205   YSTAN. DEV.= 0.071
   CORRELATION COEFFICIENT=      -0.78772666


     MICRO-DENSITOMETER METHOD            LINE NUMBER(S)=  6

BB=     -0.10596548   CC=      0.36929877   NUN= 3
X(I)=     5.4000    XX=     4.2617    XDIF=     1.1383
Y(I)=     0.9210    YY=     0.8163    YDIF=     0.1047
X(I)=     5.5000    XX=     4.4480    XDIF=     1.0520
Y(I)=     0.9030    YY=     0.8077    YDIF=     0.0953
X(I)=     5.6000    XX=     6.1123    XDIF=    -0.5123
Y(I)=     0.7570    YY=     0.7992    YDIF=    -0.0422
X(I)=     5.7000    XX=     5.6382    XDIF=     0.0618
Y(I)=     0.7960    YY=     0.7908    YDIF=     0.0052
X(I)=     6.0000    XX=     7.0555    XDIF=    -1.0555
Y(I)=     0.6850    YY=     0.7661    YDIF=    -0.0811
X(I)=     6.3000    XX=     7.1524    XDIF=    -0.8524
Y(I)=     0.6780    YY=     0.7421    YDIF=    -0.0641
X(I)=     7.1000    XX=     7.7262    XDIF=    -0.6262
Y(I)=     0.6380    YY=     0.6818    YDIF=    -0.0438
X(I)=     7.6000    XX=     7.5795    XDIF=     0.0205
Y(I)=     0.6480    YY=     0.6466    YDIF=     0.0014
X(I)=     8.5000    XX=     7.7262    XDIF=     0.7738
Y(I)=     0.6380    YY=     0.5878    YDIF=     0.0502

      XSTAN. DEV.= 1.087   YSTAN. DEV.= 0.145
   CORRELATION COEFFICIENT=      -0.79501882
```

MAGNETIC TAPE METHOD NUMBER OF PIXEL(S)= 1

BB= 0.20175720 CC= 1.92411720 NUN= 4

X(I)=	9.9000	XX=	10.5886	XDIF=	-0.6886
Y(I)=	58.0000	YY=	50.4768	YDIF=	7.5232
X(I)=	4.8000	XX=	5.0572	XDIF=	-0.2572
Y(I)=	19.0000	YY=	18.0393	YDIF=	0.9607
X(I)=	6.8000	XX=	6.7989	XDIF=	0.0011
Y(I)=	27.0000	YY=	27.0062	YDIF=	-0.0062
X(I)=	5.0000	XX=	5.0572	XDIF=	-0.0572
Y(I)=	19.0000	YY=	18.7821	YDIF=	0.2179
X(I)=	5.8000	XX=	5.5532	XDIF=	0.2468
Y(I)=	21.0000	YY=	22.0720	YDIF=	-1.0720
X(I)=	7.7000	XX=	6.2151	XDIF=	1.4849
Y(I)=	24.0000	YY=	32.3835	YDIF=	-8.3835
X(I)=	5.4000	XX=	6.2151	XDIF=	-0.8151
Y(I)=	24.0000	YY=	20.3607	YDIF=	3.6393
X(I)=	10.0000	XX=	10.6733	XDIF=	-0.6733
Y(I)=	59.0000	YY=	51.5055	YDIF=	7.4945
X(I)=	8.7000	XX=	7.9414	XDIF=	0.7586
Y(I)=	34.0000	YY=	39.6228	YDIF=	-5.6228

XSTAN. DEV.= 2.047 YSTAN. DEV.= 0.440
CORRELATION COEFFICIENT= 0.93895130

MAGNETIC TAPE METHOD NUMBER OF PIXEL(S)= 2

BB= 0.16010599 CC= 2.41294530 NUN= 5

X(I)=	9.9000	XX=	10.3968	XDIF=	-0.4968
Y(I)=	59.0000	YY=	54.4888	YDIF=	4.5112
X(I)=	4.8000	XX=	4.2353	XDIF=	0.5647
Y(I)=	22.0000	YY=	24.0817	YDIF=	-2.0817
X(I)=	6.8000	XX=	5.2787	XDIF=	1.5213
Y(I)=	26.0000	YY=	33.1707	YDIF=	-7.1707
X(I)=	5.0000	XX=	5.5144	XDIF=	-0.5144
Y(I)=	27.0000	YY=	24.8653	YDIF=	2.1347
X(I)=	5.8000	XX=	4.7788	XDIF=	1.0212
Y(I)=	24.0000	YY=	28.2632	YDIF=	-4.2632
X(I)=	7.7000	XX=	7.8112	XDIF=	-0.1112

```
     Y(I)=   39.0000    YY=   38.3119   YDIF=    0.6881
     X(I)=    5.4000    XX=    7.4824   XDIF=   -2.0824
     Y(I)=   37.0000    YY=   26.5099   YDIF=   10.4901
     X(I)=   10.0000    XX=   10.1814   XDIF=   -0.1814
     Y(I)=   57.0000    YY=   55.3682   YDIF=    1.6318
     X(I)=    8.7000    XX=    8.4210   XDIF=    0.2790
     Y(I)=   43.0000    YY=   44.9642   YDIF=   -1.9642

        XSTAN. DEV.= 2.047  YSTAN. DEV.= 0.368
   CORRELATION COEFFICIENT=      0.89163342


     MAGNETIC TAPE METHOD             NUMBER OF PIXEL(S)= 3

 BB=      0.07443128  CC=      3.08453320  NUN= 6
     X(I)=    9.9000    XX=   10.2862   XDIF=   -0.3862
     Y(I)=   47.0000    YY=   45.6682   YDIF=    1.3318
     X(I)=    4.8000    XX=    4.2545   XDIF=    0.5455
     Y(I)=   30.0000    YY=   31.2432   YDIF=   -1.2432
     X(I)=    6.8000    XX=    5.1215   XDIF=    1.6785
     Y(I)=   32.0000    YY=   36.2582   YDIF=   -4.2582
     X(I)=    5.0000    XX=    4.6950   XDIF=    0.3050
     Y(I)=   31.0000    YY=   31.7118   YDIF=   -0.7118
     X(I)=    5.8000    XX=    4.6950   XDIF=    1.1050
     Y(I)=   31.0000    YY=   33.6575   YDIF=   -2.6575
     X(I)=    7.7000    XX=    8.4513   XDIF=   -0.7513
     Y(I)=   41.0000    YY=   38.7703   YDIF=    2.2297
     X(I)=    5.4000    XX=    8.1195   XDIF=   -2.7195
```

Y(I)=	40.0000	YY=	32.6702	YDIF=	7.3298
X(I)=	10.0000	XX=	9.7020	XDIF=	0.2980
Y(I)=	45.0000	YY=	46.0094	YDIF=	-1.0094
X(I)=	8.7000	XX=	8.7750	XDIF=	-0.0750
Y(I)=	42.0000	YY=	41.7661	YDIF=	0.2339

XSTAN. DEV.= 2.047 YSTAN. DEV.= 0.179
CORRELATION COEFFICIENT= 0.85227706

MAGNETIC TAPE METHOD NUMBER OF PIXEL(S)= 4

BB= 0.03375640 CC= 3.46898590 NUN= 7

X(I)=	9.9000	XX=	8.6566	XDIF=	1.2434
Y(I)=	43.0000	YY=	44.8433	YDIF=	-1.8433
X(I)=	4.8000	XX=	3.3929	XDIF=	1.4071
Y(I)=	36.0000	YY=	37.7512	YDIF=	-1.7512
X(I)=	6.8000	XX=	5.7641	XDIF=	1.0359
Y(I)=	39.0000	YY=	40.3879	YDIF=	-1.3879
X(I)=	5.0000	XX=	2.5584	XDIF=	2.4416
Y(I)=	35.0000	YY=	38.0069	YDIF=	-3.0069
X(I)=	5.8000	XX=	2.5584	XDIF=	3.2416
Y(I)=	35.0000	YY=	39.0473	YDIF=	-4.0473
X(I)=	7.7000	XX=	10.0033	XDIF=	-2.3033
Y(I)=	45.0000	YY=	41.6337	YDIF=	3.3663
X(I)=	5.4000	XX=	11.2915	XDIF=	-5.8915
Y(I)=	47.0000	YY=	38.5236	YDIF=	8.4764
X(I)=	10.0000	XX=	7.9595	XDIF=	2.0405
Y(I)=	42.0000	YY=	44.9949	YDIF=	-2.9949
X(I)=	8.7000	XX=	11.9152	XDIF=	-3.2152
Y(I)=	48.0000	YY=	43.0631	YDIF=	4.9369

XSTAN. DEV.= 2.047 YSTAN. DEV.= 0.125
CORRELATION COEFFICIENT= 0.55436990

APPENDIX-V

FIELD DATA:RAJASTHAN REGION(CCT METHOD)

S.NO.	LONGITUDE (DEGREES)	LATITUDE (DEGREES)	LINE NO.	PIXEL NO.
1.	71.810000	25.350000	179	242
2.	72.252778	25.244444	235	928
3.	72.516666	25.202778	236	1328
4.	72.466666	25.202778	248	1256
5.	72.425000	25.200000	261	1197
6.	72.388889	25.183333	271	1296
7.	72.136111	25.233333	278	764
8.	72.427778	25.183333	285	1208
9.	72.175000	25.222222	286	825
10.	72.477777	25.166667	299	1288
11.	72.022223	25.216667	328	607
12.	72.022223	25.211111	337	609
13.	72.131945	25.193056	338	776
14.	72.044444	25.205555	340	644
15.	72.177778	25.177778	351	849
16.	72.227777	25.147222	385	935
17.	72.019444	25.155555	419	630
18.	72.352777	25.100000	426	1136
19.	72.183333	25.119444	436	883
20.	72.710000	25.190000	438	167
21.	72.116667	25.122222	447	785
22.	72.280556	25.091667	455	1035
23.	72.094444	25.119444	456	754
24.	72.041667	25.125000	460	675
25.	72.441667	25.058333	467	1283
26.	72.191667	25.086111	483	909
27.	72.075000	25.100000	489	734
28.	72.005555	25.105556	497	631
29.	72.402778	25.036111	509	1237
30.	72.361111	25.036111	519	1177
31.	72.061111	25.077778	525	724
32.	72.352777	25.027778	533	1168
33.	72.063889	25.058333	553	737
34.	72.388889	25.001667	563	1232
35.	71.850000	25.040000	629	435
36.	72.016666	25.002778	646	692
37.	71.690000	25.010000	709	216
38.	71.783334	25.866667	900	414
39.	71.650000	25.650000	1251	314
40.	72.020000	24.520000	1360	909
41.	71.625000	24.363000	1682	402
42.	71.800000	24.090000	2047	776
43.	71.600000	24.066000	2127	494

REFERENCES

1. William A. Lidster (Regional Research Coordinator Regional Officer, U.S. Burea of Reclamation Denver, Colorado 80225).

   Fred A. Schmer, Dennis W. Ryland, and Donald G. Moore (Remote Sensing Institute South Dakota State University Brookings, South Dakota 57006)

   "Remote-Sensing Techniques for Determining Water Table Depths in Irrigated Agriculture".

2. Grimaldi, J.E. and Waltz, F.A., "SADE - A Remote Sensing System", Management and Utilization of Remote Sensing Data - ASP Symposium Preceedings, Sioux Falls, South Dakota, October 29 - November 1, 1973.

3. Kaveriappa, G and Nelson, Gl, "Unsupervised Iterative Clustering in Pattern Recognition", SDSU-RSI-73-11, Remote Sensing Institute, Brookings, South Dakota, May, 1973.

4. Serreyn, D.V. and Nelson, G., "The K-Class Classifier", SDSU-RSI-73-08, Remote Sensing Institute, Brookings, South Dakota, May, 1973.